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Project leader:	N Tillett, Silsoe Research Institute, Dr Tony Webster, HRI East Malling
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Summary

In this study we have reviewed labour saving aids and strategies for UK apple and pear production. Where appropriate the authors have also drawn from their own areas of technical expertise (fruit science and engineering) in proposing future R&D needs. In making recommendations we have attempted to take into account the economic implications of and major changes in management strategy. The study focuses on the three main costs in apple and pear production, pruning/training, flower/fruitlet thinning and harvesting.

It is concluded that mechanised alternatives to hand thinning at blossom time offer the most scope for short/medium term labour saving. Specific techniques considered worthy of consideration include, strimming, high pressure water and hot air. Thinning at the fruitlet stage is thought to be rather more expensive to develop but would be best based on spiked drum shakers. In the longer term an approach based on selective use of both mechanised blossom and fruitlet thinning is thought to offer the best prospects.

Mechanised pruning would seem to offer the second most promising area for labour reduction. Strategies based on cutter bars to externally shape trees combined with hand pruning are thought to offer the best short-term prospects. A study of the effectiveness of current cutter bar systems and possible alternative cutting mechanisms is suggested. It is further proposed that some mechanised pruning within the tree structure could take place with appropriately structured trees and cutting mechanisms.

The report is not optimistic about the prospects for mechanical harvesting of fresh market fruit. Robotic technology is currently too expensive and technically not sufficiently advanced. Other mechanised techniques would rely on expensive changes to trellis based training systems and would not necessarily offer the quality of product demanded by the UK fresh market. There may be some benefit in more growers considering the commercially available harvesting aids against their own specific situations. Developments in the use of dwarfing rootstocks to bring tree height down and avoid the use of ladders would be of particular benefit in pears.

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Introduction

Currently, apple and pear producers in many countries of the world are experiencing problems of economic loss or very low profitability. These problems are particularly acute in the UK where resource costs (especially labour) are often higher and yield productivity lower than in other countries competing in the same markets with the same cultivars. The main reason for the recent decline in the profitability of apple and pear producing enterprises is the current overproduction throughout the world and the consequent depression in market prices. Very significant increases in apple production in China have had a major impact on the world market supply and the prices realised for apples. Reduced demand in some countries in Asia, due to the weakness of their economies, has also contributed to the problem The problem may exacerbate in the future, if countries formerly in the eastern bloc of Europe gain improved access to the EU markets.

To alleviate this situation UK apple and pear producers will need to achieve one or more of the following:

a) increase the quantities of quality fruits they produce per unit resource cost of production,
b) find some way of gaining a premium for their products in the markets or
c) reduce imports of cheaper fruits or win government subsidies to aid production.

As the options within c) above are extremely unlikely to happen in the present political climate, the only possible solutions must involve a combination of a) and b) above. This project will focus on a) i.e. reducing the costs of apple and pear production. However, it should be taken into account that operations conducted using physical/mechanical rather than chemical aids may also increase the value of the product in the ever increasing market for fruits that are produced using the minimum of chemicals.

The main resource costs (variable costs) in the production of apples and pears are associated with the labour requirements. Most labour is used in the harvesting, pruning and thinning of the crops. The aim of this project is to review research and development throughout the world on reducing labour costs in apple and pear production and to recommend/prioritise areas for future R&D to assist UK producers.

Project Objectives:

1. To determine what scientific research and commercial development has been undertaken throughout the world during the last 10 years on orchard systems, management and mechanisation aimed at reducing labour costs in fruit orchards. The focus will be on pruning/training, thinning and harvesting costs.
2. To identify and prioritise those ideas/systems/products that might be applicable to UK apple and pear production.
3. To suggest priorities in future R&D focused on reducing labour costs in apple and pear production

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Work Undertaken:

A literature search/review has been conducted on labour saving aids/strategies developed, which have potential for use in UK apple and pear production. The original plan was to review literature over the previous 10 years. However, this was extended back to the last 30 years, as a significant amount of work was conducted in the 1970s and 1980s. Appropriate data bases and other sources of scientific literature were used. The project supervisors have also utilised their personal knowledge and, where appropriate, their networks of contacts throughout the world.

Having taken account of the literature review, the proposers have endeavoured to identify and prioritise possible future strategies for achieving worthwhile reductions in labour costs in apple and pear production. This takes account of the likely economic implications of any major change in management strategy (e.g. the substitution of labour with machinery costs). Mention is also made of the probability of achieving commercial manufacture of any mechanised aid proposed. Finally, it identifies the future R&D needed to develop and achieve the recommended priorities.

As noted above the study focuses on three main costs in apple and pear production, namely i) pruning/training, ii) flower/fruitlet thinning and iii) harvesting. Each of these three management cost areas are reviewed separately and within each area there are sub sections covering a) current systems in use, b) their costs (economics), c) strategies attempted in the UK and abroad to reduce their costs and d) future strategies considered worthy of further investigation.

The study has concentrated on seeking solutions to the problems appropriate for implementing with traditional spindle systems. However, mention is also made of possible strategies based on more novel systems of pruning/training or based on trees with novel branch architecture.

1. Pruning and Training

1.1 Current Systems of Pruning and Training

1.1.1. Objectives of pruning and training apple and pear trees

The objectives of pruning and training commercial apple and pear trees are as follows:

i) To establish a balance between the production of new flower buds (and their associated fruits) and the production of new shoot growth
ii) To stimulate the production of strong flower buds capable of setting efficiently and producing large quality fruits
iii) To remove vigorous, upright shoots which are unproductive and compete/shade more productive parts of the tree canopy
iv) To remove diseased, or damaged shoots.
v) To either moderate or stimulate the growth of new shoots, so as to maintain trees with their allotted canopy space within the orchard.

To achieve all of the above, considerable skills are required on the part of those conducting the pruning. Equipment capable of simulating all of the above is likely to be prohibitively expensive. However, some of the pruning operations may be amenable to a more simplistic approach.

1.1.2. Pruning Methods

The methods of pruning employed with apples and pears are worthy of mention, as they influence the possibilities for mechanisation.

<u>Dormant season (winter) pruning</u>
The majority of pruning is carried out in the winter or early spring between leaf fall and bud burst, when the trees are dormant. This is referred to as **dormant or winter season pruning**. Most of this pruning is carried out currently by hand. Some equipment aids are also used to speed up this hand pruning and/or to make it ergonomically more acceptable. A few growers are experimenting with increased mechanisation (see below).

The objectives of this winter pruning are to remove branches/shoots that are a) over vigorous, b) unproductive, c) ill positioned, d) diseased or e) damaged. An additional goal is to stimulate the production of new branches, which will produce fruits in subsequent years; this procedure is known as **renewal pruning**.

The aim is to produce branches of two, three and occasionally four-year-old wood on which flowering spurs or short branches with terminal flower clusters are formed. On what are referred to as tip bearing varieties (e.g. Bramley's Seedling), the terminal flower buds on short shoots (e.g. brindilles) are most important, whilst spur flower buds are more important on varieties such as Cox and Gala. With pears, the strongest flower buds are formed in flower clusters on the terminals of shoots, and these are the most likely to set and to produce the largest fruits. Nevertheless, spur flower buds are also important on pears and contribute significantly to the yield.

Flowers formed within the basal leaf axils of one year old shoots are generally less desirable. These axillary flower buds fail to set on some varieties (e.g. Cox), have short effective pollination periods (EPPS) and may produce small fruit size on others.

Summer pruning

Pruning is also carried out occasionally during the summer months. The aim here is to remove vigorous upright current season's shoots, which are shading fruits on the tree and reducing their potential to develop adequate colour. Trees that are maintained with a good balance of shoot growth to fruit production should require the minimum of this **summer pruning**. All summer pruning is carried out by hand and no mechanical aids are used.

In most modern systems of pruning adopted with mature cropping apple and pear trees current or previous seasons shoots selected for pruning are either removed entirely back to their bases or the majority is removed to leave a short branch stub from which a replacement branch can develop. Heading back cuts (by 1/3 or 2/3), often recommended in home garden systems of pruning, are rarely used on mature trees in commercial production, although such cuts may be used in the formative years on young trees.

Although pruning can be and frequently is used as a method of reducing tree size, it is rarely efficient in this goal. Severe branch pruning, unless balanced with complementary root pruning, only serves to stimulate the tree to grow most vigorously in the subsequent season and yields are greatly reduced. Pruning is best used to stimulate trees to grow more shoots where cropping has become excessive and flower bud quality poor or to remove badly positioned, damaged or diseased shoots/branches.

1.1.3 Training Methods

All modern systems of apple and pear production rely heavily on the appropriate training of the trees. Training shoots towards the horizontal or even below the horizontal reduces the vigour of shoot growth and channels the trees resources into forming more flower buds and these flower buds are often of increased quality (i.e. more likely to set and produce large fruits). This principle is the basis of all modern training systems.

Many variations and systems of tree training have developed over the last 50 years, all of which involve branch bending. They differ in the overall tree architecture and shape achieved at maturity and can be divided into two main types; spindle and trellis systems.

Spindle systems (free spindle, slender spindle, North Holland spindle, central axis, Euro or super spindle and Hytek, etc) mostly have a single central leader (trunk) and tiers of branches emerging from this leader. In most of the spindle systems the lowest branch tiers are the most extensive and the trees take on the shape of a Christmas tree at maturity. In the Eurospindle or Super Spindle systems, which gained some popularity in the 1990s, the trees are grown as pillars with less difference in branch length between the base and the top of the tree.

Choice amongst the various spindle systems should be based on climatic conditions, the relative costs/availability of resources (trees, land, labour and capital), skill levels available and the grower's attitude to risk taking. Unfortunately, it is often governed more by current fashion.

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Most apple trees currently grown in the UK are trained to a Slender Spindle or North Holland spindle system, although a few growers have experimented with Euro spindles.

Trees trained to Trellis systems have branches which are trained into more regular planar configurations using posts and wires in various configurations. Examples of trellis systems are the V (e.g. Tatura) trellis, the A frame and the Lincoln Canopy . Most pruning and all training on trellis systems is still conducted by hand, although some mechanisation has been attempted on the Tatura (V) trellis (Young and Jerie, 1984) Van den Ende *et al*, 1987). Trellis systems are not popular currently in the UK, largely on account of the high costs needed for the post and wire supports.

1.1.4 References

Details of the various training systems could be of importance to engineers endeavouring to mechanise the labour operations associated with each system/variety. For this reason, some references are given below, which detail some of the principles associated with pruning and training and also the practices involved in each system:

Pruning principles:	Ferree, (1989); Brunner (1990); Robinson and Lakso, (1991); Robinson *et al.*, (1993); Lauri and Lespinasse (1999); Lauri and Lespinasse, (2001)
General systems descriptions:	Forshey *et al* (1997); Mika (1992); Wertheim, (1980)

The Systems

Slender spindle	Wertheim, (1970); Jackson and Palmer (1999)
Central Axe (Axis)	Lespinasse and Delort (1986); Jackson and Looney (1999)
Solaxe	Lauri and Lespinasse (1999)
Hytek	Barritt (1992)
V and Y Trellis	Robinson and Lakso, (1991); Van den Ende *et al.*, (1987)
Lincoln Canopy	Jackson and Looney (1999)

The crops/varieties

Pears	Wertheim (edit) (1990); Masseron &Trillot (1993)
Cider apples	Williams (undated)
Cox	Neuteboom and Withnall (1998)
Gala	Worraker and Withnall (1997); Anon (1995)
Braeburn	Anon (1995)

1.2 Economics of Pruning and Training

Figures provided by ADAS and FAST are roughly in agreement concerning the costs of pruning and training apple trees in the UK.

The annual costs of winter (dormant season) pruning of apples are thought on average to be:

Bramley's Seedling	£150 per acre i.e.	£330 per hectare
Cox's Orange Pippin (and sports)	£200 per acre i.e.	£440 per hectare
Gala (and sports)	£200-300 per acre i.e.	£440 - £650 /ha

No figures are available for pears but it should be assumed that pruning costs are similar to those of apples.

Tying down should only amount to a significant cost per annum during the first few years following planting of the trees. In these first three or four years, it can amount to £200 to £300 per acre or £440 to £650 per hectare per annum.

Summer pruning, if required, can amount to £50 to £100 per acre or £120 to £240 per hectare per annum.

All of the above values are for the labour and supervision required but they take no account of depreciation on any machinery used or enterprise overheads.

Most winter pruning is carried out either by full or part time regular labour employed by the enterprise and not by unskilled casual labour. However, many farms now employ specialist contractors to carry out their pruning.

The perception, when this study was initiated, was that the labour requirements and hence costs of pruning and training apple and pear trees were high in relation to most other component costs of apple and pear production.

Figures collected several years ago and provided by FAST, show the total labour hours required for tree training in the first six years following planting and how this is influenced by the tree planting densities.

Labour Hours needed (per acre) for Tree Pruning and Training

Year*	No of trees per acre					
	200	300	600	800	1100	1400
1	8	12	24	32	44	56
2	8	12	24	32	44	56
3	16	20	24	32	44	56
4	24	24	28	40	40	40
5	40	40	40	40	36	36
6	40	40	40	40	34	34

* following planting tree in the orchard

At year 6, the estimated labour costs for pruning and training are, therefore, likely to amount to between 30% and 40% of the total labour costs involved in apple growing, (but this total excludes the costs of harvesting and subsequent grading etc).

In comparisons of the costs associated with different pruning/training systems conducted in Canada several years ago (Quamme *et al.*, 1997) it was found that the labour efficiency of the slender spindle system (i.e. the labour units related to the yield output) were slightly poorer than for three other systems (a trellis, vertical axis or central leader). This reduced labour efficiency was attributable to more detailed training on the slender spindle trees. However, the slender spindle and vertical axis systems produced higher yields and better returns than the trellis and the central leader systems. Similar studies, performed in Michigan, USA, confirmed the higher labour costs of growing trees on the slender spindle system (compared with vertical axis and central leader systems) but showed also the reduced costs of harvesting with the former system (Perry, *et al.*, 1997)

1.3 Strategies Attempted in the UK and Abroad to Reduce Costs of Pruning and Training

1.3.1 Pruning Aids:

Pruning is a repetitive task that can require considerable force and awkward movements. Concerns about repetitive strain injury (RSI) and a wish to maximise working hours have prompted the development of pruning aids. Two approaches are possible and are often used in combination. The first is to improve the ergonomics of handle design. This can considerably reduce fatigue, but can still leave operators engaged in prolonged use vulnerable to medical problems such as RSI. The second approach uses an external power source to reduce the manual effort required to operate secateurs. This further reduces fatigue and allows pruning by secateurs on larger branches without recourse to saws. Systems of this type have been available for many years (e.g. Guarella, 1972 [in peaches]) and use a variety of power sources such as pneumatic, hydraulic or most recently electrical. The advantage of the latter, such as those marketed by Felco (www.felco.ch), is that they eliminate trailing pipes by running from a battery pack carried on a belt. Other makes include Pellenc SA (www.pellenc.com) who produce electrically assisted secateurs that are widely used in pruning vines. The same company also markets electrically operated tying tools for vines to reduce the time and effort involved in training. These are unlikely to be of direct use in apples and pears except when tying to wires, but some of the principles may be adaptable.

The use of pruning aids, whilst very successful in reducing the incidence of medical problems such as RSI, is not thought to improve short-term work rate.

1.3.2. Mechanical pruning

The nature of the pruning operation in apples and pears does not lend itself to simplistic mechanised approaches, as wood must be removed selectively from within the structure as outlined above. However, attempts have been made to conduct part of that operation mechanically with a view to speeding up a subsequent manual pass. Zocca (1980) describes a system for palmette trained apple trees in Italy using a circular saw based cutting mechanism. Van den Ende *et al* (1987) working on Australian Tatura Trellis trained cling peach trees used a semi-automatically positioned double reciprocating cutter mechanism with standard serrated hay mower knife sections. The machine worked quite well in Australian conditions but was limited in its efficiency due to the angle of some of the braches on the trellis. The speed of operation was 1 to 2 ha of trellis pruned in an eight hour day (Young and Jerie, 1984).

After setting external shape by removing branches at the tree periphery, follow up hand pruning is required to open up the canopy and to remove stumps of obsolete and unproductive old wood. The hand pruning stage is very necessary to avoid a thick thatch developing that reduces fruit quality due to insufficient light penetration. A few UK growers have recently tried this approach to winter pruning using a tractor mounted reciprocating cutter bars. Although reports suggest that this strategy has reduced costs, the cutters are prone to jamming and sometimes tear the branches badly exposing the tree to disease. It is believed that some more efficient cutting device is needed.

Considerably more progress has been made with the relatively simpler task of pruning vines grown on a studded cordon (Lisa, 1996). Companies like Pellenc SA offer commercial tractor mounted machines consisting of a double set of counter rotating cutting disks one set either side of the cordon. External casings around each set of disks are arranged such that wood to be cut can pass between them, but the larger stakes force the two sides apart leaving the stakes and main stem uncut. The blades that operate on a horizontal plane can then cut all vertical wood at a manually controlled height, even close to the stakes. In principle a similar approach could be applied to apples and pears, though it would be necessary to train trees into a similar two-dimensional cordon.

In crops other than apple, where pruning in the summer, rather than in the winter is the norm, mechanisation has occasionally proved successful. With the sour cherry (*Prunus cerasus* L.), which unlike apples and pears crops primarily from axillary flower buds on one-year-old wood, summer hedging of the large trees has proved quite successful (Flore, *et al.*, 1996). In Michigan, USA, where the principal sour cherry variety is 'Montmorency', summer hedging of the trees has become standard practice. Work by Michigan scientists (Kesner, *et al.*, 1981; Kesner and Nugent, 1984) showed that trees responded well if the sides of the trees were hedged with a double sickle bar to remove one third to one half of the current seasons growth. The mechanical hedging was carried out 40-47 days after petal fall on the flowers, just before the final swelling of the fruits. At this time spur growth had stopped and terminal leaf emergence had slowed. This timing is important, because if the operation is carried out earlier it stimulates unwanted re-growth of the shoots. Hedging of Montmorency sour cherries at this time is reported to increase fruit size, make ripening more uniform and increase the numbers and quality of new flower buds produced. The most successful tree shape for use with such hedging systems is an inverted V with tree rows orientated north-south. Even on these sour cherry trees, hedging increases the leaf density in the periphery of the tree crown canopy and supplementary, albeit minimal, pruning to remove a few major branches every 1-2 years is recommended.

Unlike the sour cherry, apples and pears crop mainly on spurs formed on 2, 3 and 4 year old wood and the use of summer pruning by mechanised hedging techniques is less appropriate. However, were techniques of trellis training adopted, such as the Tatura Trellis, summer hedging could have a small role to play in apple and pear culture.

1.3.3. Alternative management strategies attempted to reduce the need for pruning and training

Use of scion cultivars with compact or spur type habit
Apple growers in the USA and Canada have for many years used clones of apple scions which exhibit less vigorous growth than the standard clones. Clones of the variety Red Delicious, such as Red Chief, Ace and Oregon Spur, all of which have been discovered as natural mutants in orchards, provide a degree of scion vigour control and may influence the labour requirements for pruning and training. Similar compact or spur-type clones of the variety MacIntosh have been used with some success in Canada. However, these two varieties are the exception, as most other spur types selected over the last 20 years have cropped less efficiently than the standard types and have often proved to be very unstable chimeras.

Fruit breeders have attempted to induce the production of compact mutants using techniques of irradiation breeding. Irradiation breeding work at Long Ashton and subsequently East Malling resulted in the selection and release of several compact clones of Bramley's Seedling in the late 1980s. However, these clones have not to date gained significant commercial acceptance. More recent irradiation breeding work conducted in Bologna, Italy has produced clones of the pear varieties Williams, Conference and Abate Fetel, all of which exhibit reduced vigour. These are currently on trial in several countries, including the UK.

All of the above spur or compact clones exhibit shortened internodes or reduced rates of shoot growth. Otherwise their branch architectures (tree shapes) are similar to those of conventional scion varieties. The exceptions to this are the columnar or Ballerina trees. All of these originate from one mutation of MacIntosh discovered in a Canadian orchard. Fortunately, this mutation proved to be dominant and when pollen was used from it, the characteristic was passed to many of the progeny. This is how the Ballerina range of varieties was produced.

The Ballerina or columnar varieties produce almost no lateral branches only fruiting spurs on a single central leader or column. No pruning is required on such trees. The problems associated with the current range of columnar types are: pronounced biennial bearing (heavy crops in alternate years and no crops in the intervening years), only average fruit quality and sensitivity to apple canker (*Nectria galligena*). Also, columnars must be planted at very high tree densities if land areas are to be used efficiently. Unless the costs per nursery tree can be reduced, planting at such high densities is unlikely to prove economically viable. For these reasons, columnar varieties have not been planted for commercial apple production

Use of dwarfing rootstocks
The vigour of shoot growth and eventual size of tree at maturity is usually controlled by use of rootstocks, a range of which offer different degrees of vigour control of the fruiting part of the tree, the scion. There is a good range of dwarfing rootstocks available for apple and this range continues to expand. Only on the poorest of soil types or where land is infected by particularly severe disease organisms are dwarfing rootstocks unsuitable. The range of stocks available for pears is still limited and pear growers must rely more heavily on pruning/training techniques for the control of tree vigour and cropping.

Although dwarfing rootstocks provide much of the necessary control of tree vigour they cannot be used in the absence of pruning and training. Although very dwarfing rootstocks, such as M.27, will, if left unpruned produce almost no new growth once mature, this is not to be recommended. The permanent spur systems on such trees produce many fruits, but these fruits are usually too small and unmarketable. Some renewal pruning is required on all apple and pear trees so as to provide new shoots on which spurs etc will eventually develop. New spurs and flower buds produce fruits of higher quality and larger size than old spurs.

Choice of rootstock does, however, influence the degree of pruning and training necessary in an orchard. Most UK apple trees are grown on M.9 which once in balance and mature should require only light renewal pruning. Trees on more vigorous rootstocks, such as MM.106 or MM.111 generally require more pruning per tree but this is compensated largely by the fewer numbers of trees planted per unit land area.

Use of chemical growth retardants

Treatment of apple and pear trees with specific plant growth regulating chemicals can achieve some of the objectives listed above for pruning and training. Growth regulating chemicals, which reduce the production of gibberellins by the tree, can reduce internode length on shoots, so reducing the vigour of shoot growth and tree size. Paclobutrazol (Cultar) has been widely used on apples for this purpose but has proved less successful on pears. Another product with the same mode of action, Cyclocel (CCC), was used successfully on pears in several European countries until recently. Both of these products reduce the need for pruning and have the additional benefit of stimulating the production of abundant high quality flowers.

Unfortunately, CCC, which was never approved for use in the UK on pears, has now been withdrawn from use in most countries. The rates necessary to achieve adequate control of tree size in pears resulted in unacceptable levels of residues in the fruits at harvest time. Similar problems have not, to date, been experienced with Cultar use on apples. However the product has a long persistence in the soil and in the tree and if applied in too strong a dose can have deleterious effects on the tree's growth and productivity.

A new plant growth regulating chemical, prohexadione-Ca shows considerable promise for use on apples and pears, following trials in several countries. This new product has the benefit of showing low persistence in the tree and soil but must, therefore, be applied several times each season to achieve adequate growth control on very vigorous trees. Whether this product proves cost effective will depend upon its eventual pricing, if and when it is released for use in the UK.

Consumer opinion tends to have swung against the use of growth regulating chemicals on fruits and this should be taken into account by growers planning to establish new orchards. Heavy reliance on the use of plant growth regulating chemicals for control of tree vigour is not to be recommended in the future.

The potential interaction of mechanised pruning and use of chemical methods of growth control are not known.

Use of root pruning or restriction techniques

It has been known for centuries that the excessive shoot growth on fruit trees could be reduced if their roots were pruned quite severely. The practice went out of fashion after Victorian times on account of the high labour demands needed to carry out the pruning.

More recently root pruning has been re-examined in trials conducted mainly in the USA and the UK. The reasoning was that if it could be shown to have useful benefits, there were now mechanical aids to root pruning (chisel ploughs etc) which could make the technique more economically viable. The results of the UK trials (Webster, unpublished) showed that root pruning caused a) significant reductions in shoot growth b) increased production of flowers c) variable effects on fruit set but d) reductions in the size of harvested fruits. This reduction in fruit size, which has been observed in trials elsewhere, is considered too severe a defect to warrant the adoption of root pruning on many of the apple varieties grown on the UK, which are inherently smaller than average in size.

Planting trees within partially permeable membranes, (root restriction), has also been attempted as an aid to moderating the excessive vigour of fruit trees. Membranes which prevent the growth of tree roots through them induce similar effects to root pruning (Webster *et al.,* 2000) Less deleterious effects on harvested fruit size are induced if membranes which girdle but do not fully inhibit roots passing through them are used (Webster, in press).

The economics of root restriction strategies for control of tree vigour and cropping have not been calculated.

1.4 Future Strategies considered worthy of further investigation

1.4.1 Mechanical Aids to Pruning

Robotic

Mechanised pruning may offer some opportunities for reduced labour input. Technically, there are two approaches. The first, full automation, would use robotic technology to sense tree layout, make intelligent decisions about what was required and then finally control cutting devices to complete the task. Steps towards such a system in vines have already been made by French (Sevila *et al*, 1990) and American (Mercurio *et al*, 1989) researchers. A member of staff at SRI has more recently been working with the French team on the image analysis and decision making aspects of the problem (McFarlane *et al*, 1997). However, even in the more straightforward task of vine pruning this work has some distance to go before a commercial product becomes available. The task is similar in sophistication to that of robotic apple harvesting and many of our comments on that topic, made later in this report, also apply to pruning. We therefore regard this as a long-term objective and not one that will yield short or medium term benefit.

Mechanised

The second approach would be to develop and improve existing mechanised pruning equipment as a means of reducing hand labour. The first and simplest task would be to improve cutter bar mechanisms such that existing approaches using cutter bars to externally shape trees can be conducted more efficiently with higher quality. Some consideration has been given to alternative cutting mechanisms. One of the most radical alternative techniques would be water jet cutting which is widely used in industry to cut a diverse range of materials such as plastics, leather and even, with the addition of abrasives, metals. The advantages lie in a clean cut that does not generate heat, an ability to stay sharp (though nozzles wear), compactness and ease of control. However, the technology is relatively expensive and would probably not perform well on flexible stems that would be deflected by the water jet itself and the jet of entrained air around it. The range is also limited. We would therefore recommend using more conventional cutting technologies in any future work.

Before proceeding with any new design of cutter bar it would be sensible to trial a range of existing mechanisms. However, the combination of requirements for high quality cut finish, high work rate and branch size range may be unique to this application, and so require some machinery development. In designing a cutter bar mechanism one challenge would be to ensure that the wood is adequately grasped so as to avoid splitting as the blade exited the branch. In the first instance it is envisaged that such cutter bars would be tractor mounted, operate on one face of the tree only and be positioned by the operator via steering the tractor. Should this relatively simple arrangement be successful it may be possible to increase work rate by pruning both sides of the trees at once.

A second task in improving mechanised pruning would be to attempt a limited amount of pruning within the tree structure further reducing, but not eliminating the need for hand pruning. The practicality of this approach would be dependent on the pruning and training done in structuring trees during their early growth. In particular it would simplify operations if the main branches to be retained were close to horizontal, reasonably evenly spaced vertically and if possible at a similar level in adjacent trees. This would allow a horizontal cutter bar penetrating the structure to remove some vertical branches without causing damage. It would be unrealistic to expect trees to be trained with complete uniformity and so it would be necessary to for an operator (the tractor driver) to provide a degree of manual guidance. The details of such a system require further thought, but it might for example be based on about four horizontal cutter bars stacked one above the other and positioned outside the tree structure. When the operator could see branches requiring pruning that lined up with one of those cutters it could be swung into position within the tree. If adjacent trees were trained such that horizontal branches to be retained were at similar levels the cutters could be left in place as the mechanism passed through several trees. Such a mechanism could be combined with a cutter bar pruning the external profile of the trees. This would increase driver workload and might usefully be combined with automatic steering of the tractor. The engineering technology of such a system is reasonably well understood and could be tackled by a competent agricultural engineering company. The greatest uncertainty would lie in the quality of the cut, the percentage of the pruning that could be done in this way, its accuracy, and the work rate that could be achieved. The last two issues would be dependent partly on the ergonomics of the operator's interface with the machine.

Despite these uncertainties the relatively high cost of pruning would seem to make such a development worthy of future consideration. Based on Young and Jerie (1984) we might expect such a device to have a capacity of 1ha/day. With a potential pruning season of 40 days the machine could be used over about 40ha per annum either by a contractor or a grower syndicate. Reducing pruning costs by (say) a third over 40ha might typically save £6000 per annum in Cox or Gala, enough perhaps to justify spending up to £15,000 per machine.

1.4.2 Alternative opportunities for reducing the costs of pruning and training

Use of scions with columnar or compact habit

This strategy has much to recommend it, as trees with minimal annual shoot growth or very determinate habit would also be more amenable to mechanised thinning and harvesting.

As stated above, most varieties with 'compact' habit have performed poorly in commerce; the main exception to this rule being the compact clones of the apple variety Red Delicious. The problems are often due to these compact types being unstable chimeral 'sports'. If genetically solid types can be produced they may have much more potential with varieties other than Red Delicious than previously thought. The new compact clones of pears produced in Bologna, Italy (Predieri, 1998) are certainly worthy of further trialing and these can be propagated using *in vitro* techniques (Predieri and Govoni, 1998).

Apple trees with columnar habit require no pruning, apart from the removal of diseased wood. However, none of the existing varieties are of sufficient quality to meet the demands of the commercial markets and more effort is needed to breed improved varieties. The problems with the existing varieties are a) average fruit quality b) poor storage potential, c) sensitivity to apple canker (*Nectria galligena*) d) tendency to biennial bearing unless thinned very efficiently and e) high costs per unit land area to establish orchards at the close tree spacings necessary and the high unit costs of trees. If these problems are to be solved it will be essential to

i) devote increased effort to breeding of columnar apple varieties which have improved fruit characteristics, are less prone to disease and biennial bearing and easier and cheaper to propagate.
ii) seek varieties that are partially columnar (i.e. with several columnar habit branches per tree). Fewer trees would be required per hectare and the orchard establishment costs should be reduced
iii) seek to isolate the columnar gene and using modern techniques of molecular biology introduce this to the popular commercial varieties of apple and pear

The ultimate success of the final strategy highlighted above, iii), will be influenced greatly by consumer attitudes to GMO fruits.

Pear varieties bred using the very compact habit variety 'Nain Vert' as one-parent produce very small conical-shaped trees, which require almost no pruning. However these grow too slowly and take many years to fill their allotted space. Fruit quality is also poor on the varieties produced to date. Such varieties seem to offer no immediate promise.

All of the above must be considered as long term solutions and will not provide immediate remedies for UK growers faced with high costs of pruning and training.

However, this strategy is worthy of further investigation. Researchers in the USA (Scorza, personal communication) have made significant progress in developing peach varieties with much reduced shoot growth and less requirement for pruning.

Use of Dwarfing Rootstocks

Although dwarfing rootstocks much reduce the vegetative vigour of apple and pear trees they do not remove the need for pruning. By inducing increased fruiting and reduced vegetative growth they do however reduce the requirement for pruning and training.

In terms of the potential to control extension shoot growth and tree vigour it can be argued that an adequate range of rootstocks already exists for apples. However, the existing range of rootstocks may not be well suited to new systems of tree management, which involve less use of herbicides and reduced availability of water. Together with climate warming these changes will create a need for new dwarfing rootstocks with greater tolerance to unfavourable soil/climatic conditions.

The range of dwarfing rootstocks for pears is very limited and very high density planting systems for this crop are not possible without recourse to use of plant growth regulating chemicals. New improved dwarfing rootstocks are needed for pears to aid the reduction in pruning costs.

Use of chemical growth retardants

Apple and pear growers in the UK are permitted to use the plant growth regulator paclobutrazol (Cultar) as an aid to controlling excessive shoot vigour on their trees. Used correctly, this product can prove very effective, particularly on apples. However, Cultar is very persistent, both in the tree and the soil, and mainly for this reason has never been approved for use in most other countries in Europe or in the USA and Canada. There must, therefore, with the move towards unification of EU regulations concerning chemical usage, be some speculation whether its use in the UK will continue in the long term.

A new product, prohexadione-Ca, which can have similar effects in controlling excessive shoot growth, is much less persistent than Cultar. However, this means that several applications each season may be necessary to achieve adequate growth control. It is likely that the manufacturers, BASF, will get limited approval for release of the product in some European countries within the next few years. The product already has limited clearance, under the brand name of 'Apogee', in the USA. It will be essential that trials are conducted on UK varieties and in UK conditions if growers are to keep abreast of their competitors in Europe and the USA.

Use of root pruning or restriction techniques

In trials conducted at HRI –East Malling and in several other countries root pruning and full root restriction has proved effective in reducing shoot growth and increasing flowering on apple and pear trees. However, fruit size has usually been reduced and this effect is very undesirable on small fruited varieties such as Cox and Gala apples and Conference pears.

Partial root restriction using membranes with larger pore sizes caused less reduction in fruit size and this method may be worth further study.

2. Flower and/or Fruitlet Thinning

If apple and pear fruits of the size and quality desired by the markets are to be produced, some method of crop load reduction will be necessary with most of the popular commodity varieties. This crop adjustment is usually referred to as flower and/or fruitlet thinning. Most varieties of apples and pears set excessive numbers of fruits and this leads to poor fruit size and poor fruit texture at harvest, and reduced floral abundance/quality in the subsequent season. Although large-fruited apple varieties such as Jonagold and Bramley's Seedling, and the pear variety Comice may require minimal or no thinning in some seasons, others, such as the smaller fruited Cox and Gala regularly need thinning.

Skilled winter pruning can reduce the need for flower and/or fruitlet thinning. Where trees produce excessive numbers of flowering spurs many of these can be removed as part of winter pruning.

2.1 Current systems of flower and/or fruitlet thinning

2.2.1 Hand Thinning

Traditionally, all thinning is carried out by hand after the risk of frost damage is passed and initial fruit set had been assured. This practice is still the most reliable method of crop load adjustment on apple and pear trees, albeit the most expensive strategy. Trees are thinned when fruitlets are between 10mm and 20mm in diameter. On most small-fruited varieties of apple the fruitlets are removed to leave one (or occasionally two) fruitlet(s) per flower bud cluster. The fruitlets left on the tree after thinning should be evenly spaced down the branches, allowing a few inches minimum between adjacent fruits. Traditionally, the fruitlets are removed using pruning scissors which cut the fruitlet stalks (peduncles). Pulling the peduncle off at its cluster base can remove or cause damage to the cluster and the fruit(s) remaining on it. However, in attempts to reduce the time taken to hand thin trees growers frequently adopt much cruder methods of fruitlet removal, which may, on occasions, cause significant spur damage.

Thinning of flowers by hand is not practised on mature orchards, due to the very high costs involved. However, in the first two years following planting flowers may be removed from young trees to prevent fruit set, alleviate fruit:shoot competition and encourage the rapid development of the tree branch canopy and the filling of the allotted orchard space.

Hand thinning is carried out by both skilled and unskilled labour.

2.2.2.Fruitlet thinning using chemicals

For many years UK growers have thinned their fruitlets using a carbamate insecticide, carbaryl (Sevin/ Thinsec). Although superseded many years ago by more efficient and environmentally safe insecticides, carbaryl has retained a place in the orchard spray calendar as an efficient fruitlet thinner of apples. Applied when apple fruitlets have grown to 12mm in diameter, carbaryl has performed well in most situations. However, in the last few years carbaryl has been withdrawn from use as a thinner in most EU countries, including the UK.

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Most of our competitors in apple production in Europe still have approval for use of alternative chemical fruitlet thinners, such as NAA, NAAM and Ethephon. Only in Germany and the UK are growers left with no approved chemical following the withdrawal of carbaryl. The registration of NAA, NAAM or Ethephon (Ethrel C) for use as fruitlet thinners in the UK is not considered likely.

No chemical thinner is approved for use on pears in the UK.

2.2.3 Flower thinning using chemicals

Traditionally in the USA, flower thinning was achieved using sprays of dinitro ortho cresol (DNOC) applied at the time of full bloom. This chemical (trade name Elgetol) has now been withdrawn from use as a thinner and alternatives have been sought.
Thinning at the time of flowering of apples and pears has, until recently, proved unpopular with UK growers. Concerns about potential damage from frost and poor fruit set has made growers reluctant to use any thinner before this risk was over.

However, a few growers have recently experimented with the use of ammonium thiosulphate as a 'nutrient' applied at flowering time (!) on orchards of apple trees, with a history of consistent over set.

No chemical is currently approved for use as a flower thinner on apples and pears in the UK.

2.2 Economics of thinning

Estimates provided by representatives of both ADAS and FAST suggest that the costs of hand thinning apple trees in the UK ranges from £150 to £300 per acre or £330 to £660 per hectare. The lower figures are applicable when the tree sets less than maximum fruit numbers, due possibly to lower than average blossom density or weather conditions unfavourable for pollen transfer and fruit set. The higher figures are associated with insufficient winter pruning to remove excessive spur clusters, high blossom density and/or ideal weather conditions for pollination and fruit set.

Figures collected several years ago and provided by FAST, show the total labour hours required for thinning in the first six years following planting and how this is influenced by the tree planting densities.

Labour Hours needed (per acre) for Thinning

Year*	No of trees per acre					
	200	300	600	800	1100	1400
1	0	0	0	0	0	0
2	4	6	12	16	18	20
3	8	12	24	32	36	40
4	20	25	32	32	40	40
5	30	35	40	45	45	45
6	45	45	45	45	45	45

* following planting tree in the orchard

At year 6, the estimated labour costs for thinning are, therefore, likely to amount to between 40% and 50% of the total labour costs involved in apple growing, (but this total excludes the costs of harvesting and subsequent grading etc).

2.3 Strategies Attempted in the UK and Abroad to Reduce the Costs of Thinning

2.3.1 New chemical aids

Chemical thinners of fruitlets

The cytokinin type chemical benzyladenine (BA) has shown some promise as a replacement for carbaryl in trials in the USA and Europe (Greene, *et al.,* 1990; Bound, *et al.,* 1991; Ferree, 1996;Webster and Spencer, 1999). However, no country in Europe has yet gained approval for its use as an apple or pear thinner and, even if approval is eventually achieved in some European countries, the approval for its use in the UK may take many years to achieve.

Chemical thinners of flowers

As noted above reductions in potential crop loading on trees can also be achieved by preventing many of the blossoms setting fruits. A number of chemical blossom thinners have been identified including ammonium thiosulphate (ATS), endothallic acid, urea, lime sulphur, sulphcarbamide (Wilthin) and pelargonic acid (Williams, 1993 and 1994; Williams *et al.,* 1995; Bound and Jones, 1997; Webster and Spencer, 1999). Most, if not all of these chemical work by desiccating the sexual organs of the flowers; the stigmas, ovaries and anthers.

Amongst these flower thinners, only the relatively simple inorganic compounds, such as lime sulphur, urea and ATS are likely to meet environmental guidelines and achieve approval in the future. Their efficacy depends significantly on weather conditions at the time of application, with warm temperatures increasing the thinning efficacy and humid weather with slow drying causing increased phytotoxicity of the spur (primary) leaves present at the time of spraying. Phytotoxicity or any significant damage to spur leaves is not desired, as these leaves are very important to the initial growth and retention of the persisting fruitlets and also to the calcium uptake by these fruitlets.

Attempts to find chemicals for thinning apples and pears that would be acceptable within organic protocols of production have to date proved largely unsuccessful. Although various oils, such as that from oil seed rape will thin at blossom time, they often cause unacceptable leaf damage or russeting of fruits.

Despite much research, chemical thinning of pear fruits is still a problem with very inconsistent results achieved in most thinning trials in the UK and elsewhere in Europe.

2.3.2 Mechanical thinning

Mechanical thinning of fruitlets

As with chemical thinning there are two opportunities to mechanically thin during the growing season, at bloom and at early fruit development. Both have been attempted, though fruitlet removal using shakers has received more attention. Much of the work on shakers as a means of thinning has been conducted on peaches (Powell et al, 1976, Glenn et al, 1994) as chemical thinning is sometimes less effective on that crop and the fruits used for canning can sustain slightly more impact bruising than fruits for the fresh market.

Another stone fruit that is occasionally fruit thinned mechanically is the prune. Californian research has shown that this is best achieved when the fruitlets are still quite small (Fitch *et al.,* 1972). Although the treatment caused some injury to the persisting fruitlets, the proportions of undersized fruits at harvest were reduced and fruit grades were improved. Further work by the same author (Fitch, 1981) noted that any type of trunk shaker was adequate for the job and no special shaker weights were considered necessary. However, as the bark slips easily when soil moisture is high in the spring, only a short shake should be given if bark and cambial damage is to be avoided.

Some success using a similar shaking strategy was also achieved on 'Victoria' and 'Czar' plums grown for fresh consumption in the UK (Woodward, 1971), although the technique was not effective in thinning clusters of fruitlets formed on the tips of long slender branches. Danish research also examined mechanical thinning of plums but noted that additional hand thinning was needed to complete the thinning (Grauslund, 1980). As in the UK work, the thinning was least effective on the ends of long non-stiffened shoots. Work in eastern Europe has shown that apricots may be thinned using a modified 'Kilby' tree shaker (Szelevenyi, 1974).

Although all of the above work was focused on stone fruits, the techniques and equipment used for mechanically thinning apples and pears by shaking is similar.

Shakers can be subdivided into two groups, the traditional impact trunk shakers and spiked drum devices that penetrate the tree structure as they vibrate. Menzies (1980) reported on trials of impact shakers in apples and pears. His results showed that the mechanised approach yielded broadly similar to hand thinning, though the action of the shaker was non-selective on fruitlet size. Hand thinning would normally aim to remove the smaller fruitlets, preferentially. It should be noted that the trees in these trials were all fairly old (40-20 years for apples and 80 years for some of the pear trials) and relatively rigid in structure which might favour performance of this technique. Menzies also stated that apple return blossom for the following season would not be improved as the thinning was conducted relatively late and initiation of next year's flower buds would have already been inhibited by the presence of excessive numbers of fruitlets early in the season.

We found no reference to the use of spiked drum type shakers being used in apples or pears, but Glenn et al (1994) reported on a comparison of this device in peaches with an impact shaker and with hand thinning. Both mechanical techniques were not selective on fruitlet size and in the first year gave the same results as hand thinning. In the second year the spiked drum shaker over thinned and the treated trees yielded less than the trees treated with the impact shaker, though this may have been due to misjudgement by the operators rather than an inherent problem with the technique. The physical difference between the spiked drum shaker and the trunk impact type lay in the duration of the shaking. The drum type produced three oscillations over less than half a second compared to a large number over 8 seconds for the trunk shaker. They speculated that the reduced energy imparted to the tree by the drum type is better for tree health particularly at the point of attachment, though the drum shaker did break some branches (0.8/tree at 0.5kph and 1.6/tree at 2.0kph).

Mechanical thinning of flowers

Attempts to thin flowers using mechanical methods have met with variable success. Some of the preliminary work was conducted on peach trees grown in the USA. Researchers based in West Virginia (Baugher, *et al.*, 1991) tested two devices, one a tree width rope curtain, which was dragged through the trees and the other a rotating rope curtain. Six trips over the tree canopy were required with the tree width curtain, whereas only one passage down the row was needed with the rotating device. This thinned peaches to approximately one flower per 9cm of fruiting shoot length. The results showed that rope curtain thinning was as effective as hand thinning. It reduced hand thinning time by 40% and increased harvest fruit weight by 10% to 20%. The performance of the rope curtain thinning attachments was negatively correlated with shoot density. Thinning was most efficient on open centre trees on which detailed pruning had been conducted to eliminate overlapping shoots.

Peaches produce their flowers before any leaves are produced and this makes such crude thinning strategies rather less damaging than on apples and pears, where spur leaves develop in synchrony with the flowers.

Driven by the needs of organic apple production an Italian team (Kelderer *et al*, 1998) has investigated the use of a strimmer type device to mechanically thin at the blossom stage. The machine manufactured in Germany by H. Gessler consists of a tractor pto driven vertical shaft the height of the trees. A number of thin plastic lines are attached radially along the length of this shaft. The tractor is driven down the row of trees grown as slender spindles in such a way that the plastic lines strim the trees removing some of the blossom. The results show that fruit numbers were reduced by between 20 and 40% compared to an un-thinned control. The Italian authors also investigated the use of a number of organically approved thinning chemicals with some success, though these had an adverse effect of fruit quality. Schroder and Link (1996) used the same Gessler machine on a mixture of super and slender spindle trained trees. In 1995, they found thinning to be very effective giving increased fruit weight. In 1996 they also found the technique to be effective, though late treatment at the balloon stage of bud development resulted in over-thinning. They also reported significant tree damage particularly to leaves and suggested that disease and other problems associated with this damage needed further investigation.

Other non-chemical flower thinning strategies

Preliminary research conducted in the USA in the late 1980s (Byers, 1989) showed that high pressure water might prove a useful tool for thinning peaches. In this work high water pressures (>3Mpa or >30bars or atmospheres) were needed to bring about effective thinning. Unfortunately, this work was not pursued in further trials.

Preliminary work conducted by the author (Webster, 1993) on plums, suggested hot air could be used to reduce fruit set by damaging a proportion of the flowers without damaging the leaves. Temperatures of approximately 60^0C caused sufficient flower damage to prevent set (see table).

The effect of treatment with hot air, applied at full bloom on the final fruit set per 100 flower buds of 'Victoria' plum trees

Air temperature at flower (^{0}C)	Duration of treatment (seconds)				
	1	2	3	4	5
51-57	7.3	11.2	8.3	5.0	2.7
67-73	3.5	7.5	8.9	0	1.8
82-85	3.5	8.2	1.5	0	0

The problem with developing this technique of hot air thinning concerned the delivery of the air at the critical temperatures to flowers of trees grown with conventional shape/branch architecture.

2.4 Future Strategies considered worthy of further investigation

It seems likely that the opportunities for chemical thinning in UK apple and pear production, either conventional or organic, will not be improved significantly in the future. Given the very high cost of hand thinning, mechanical alternatives should be sought. Uncertainty on the long term effects of mechanical techniques with respect to tree damage and risk of biennial bearing, combined with the risks associated with late frosts and over thinning, suggest that a number of options should be considered in the short term. In any case, it is possible that the best solution may prove to be a flexible combination of techniques covering both blossom and fruitlet thinning.

Mechanical thinning of fruitlets

Trunk impact shaker techniques are based on commercially available harvesting machinery. It should, therefore, be possible to obtain equipment that, with some modification, could be adapted to conduct trials in UK orchards. If trunk or limb shakers were employed, it would be important to measure the effects of different shaking treatments (clamp pad design, length of shake and resonance) on trunk/limb damage to trees of different ages and varieties. Bark and cambium damage, due to excessive shear, torsion and compression can be a problem, if equipment if badly designed or improperly used. Such studies have proved critical for the Michigan sour cherry industry (Brown and Kollar, 1996).

The tree size and architecture associated with the relatively young UK orchards grown as slender spindles would appear to be rather better suited to the spiked drum approach that does not rely on strong stiff trees. The spiked drum shaker used by Glenn *et al* (1994) was based on an experimental device built by Peterson *et al* (1989) for blackberry harvesting. It is not clear if this particular machine ever reached commercial production. Further investigation would be required to establish if any commercial equipment is available that could be adapted. Alternatively equipment could be constructed specially for this task, as the basic operating parameters have been published, though this would be relatively costly.

Mechanical/physical thinning of flowers

The results obtained with rope curtains for thinning peach blossoms (Baugher, *et al.,* 1991) although promising, appear rather crude for use on apple and pear trees. Peach trees flower primarily on one-year wood (axillary blossoms) whilst apples and pears flower more on spurs. It is reasoned that ropes would have the potential to cause excessive damage to this spur system and to provides sites for entry of damaging diseases.

The reasonably promising results obtained with strimming blossom would seem to encourage consideration of thinning at blossom time. Presumably, it would be possible to purchase or hire a Gessler thinning machine (Kelderer *et al.*, 1998) for trials under UK conditions. It would, however, seem preferable to use a technique that did not concentrate its action on the outer surface of the tree. It would also seem likely that a less violent tool than a strimmer should be able to inflict sufficient damage to prevent set of physically fragile blossoms. A method that exploits the relative robustness of leaves and tree compared to flowers would seem to offer a better compromise.

High pressure water jets may offer such a medium (Byers, 1989). Water jet thinning could be conducted in a number of ways. A very intensive treatment might be used to eliminate almost all blossoms at an early stage with a view to obtaining fruit set on later blossoms. A less intensive treatment could be applied to the whole tree and adjusted to knock out a certain percentage of blossoms based on experience. An intensive treatment could be conducted on parts of the tree so that some areas have all blossom removed and others are unaffected. This could be done at a variety of scales and on a number of patterns. Treatment should be relatively fast and so it might be acceptable to have a strategy based on multiple treatments. If the high pressures needed to thin peach blossoms in the USA were found to be required on apples and pears, it is likely that the water would need to be delivered within some protective head, to avoid operator injury. Incorporation of a high-pressure water thinner within a tunnel sprayer is one possibility.

Hot air thinning is also a possibility worthy of further investigation (Webster,1993). This also would require incorporation within a tunnel type sprayer for it to be most effective. Alternatively, trees would probably need to be grown with all of their flowers in a single plane, as with the V systems. This would allow precise delivery of the hot air close to the blossoms.

Although more expensive, it would be possible to envisage an intelligent blossom thinner that used computer analysis of video images of the tree to assess how much blossom was present and to conduct treatment accordingly. The intelligent thinning option is probably only realistic at blossom time, as petals, unlike fruitlets, are more easily detectable at this time. An intelligent thinner could operate in a variety of ways and research would be needed to investigate which gave the most cost effective results. For example, at a closely spaced linear array of individually selectable water jet nozzles could be tractor mounted on a vertical post such that any pattern of treatment could be applied as the tractor progressed along the row in the manner of a large ink jet printer. SRI has already developed a similar system operating horizontally for the spot treatment of vegetable transplants (Tillett et al, 1998). A development of that system used for the guidance of inter-row cultivation is now in commercial production.

Equipment to establish the feasibility of water jet thinning could be investigated with low cost high pressure cleaning equipment and appropriate nozzles. If initial ad-hoc trials looked promising a more scientific trial could be conducted to establish the response of blossom to water jet parameters such as pressure, nozzle size, range etc. The robustness of the leaves and tree to these treatments would also need to be established. Options for intelligent thinning do not need to be pursued until work with water jets has been completed, as a simple approach may prove adequate.

The loss of chemical thinners will result in a considerable increase in demand for hand labour within the UK industry if mechanised alternatives cannot be found. The availability of that labour and its susceptibility to RSI and similar ailments is in question. Otherwise, the economics of mechanised thinning are very similar to that outlined above for pruning, except that timing is much more critical. This is particularly true for blossom thinners. Consequently the number of days with an opportunity for thinning over which equipment can be justified will be relatively small, say 20 days. This means that it might be worth investing only half as much in an individual thinning machine as in a pruner. On the other hand if workrate is similar, twice as many machines will be required. Overall the two problems are of very similar scale within the UK industry and worthy of comparable research effort, though shortage of labour for thinning may favour that topic.

3. Harvesting

Harvesting is one of the most costly and labour requiring operations in the production of apples and pears. Most growers employ visiting workers from overseas (usually eastern Europe) to supplement their permanent labour to aid them with their harvesting. Nevertheless, it is often difficult to secure adequate labour and the supply of students and others from eastern Europe may not be available in the long-term future.

3.1 Current systems of fruit harvesting

3.1.1. Equipment used

All the harvesting of apples and pears for the fresh market is carried out by hand in UK orchards. However, harvesting of apples and pears for cider and perry production is already mechanised.

In orchards producing fruits for the fresh market, the fruits are picked by hand into a picking bucket strapped around the waist of the picker. Once full the buckets of fruits are walked to a bulk bin placed between the rows of trees in the orchard. The fruit is deposited into the bin by releasing the canvas base of the picking bucket and allowing the fruit to carefully flow into the bin. The bulk bins are placed at intervals in the row estimated to equate to the volume of fruit on the trees, such that all bins are filled but pickers do not waste undue time walking to the bins.

Most modern apple orchards, grown on dwarfing rootstocks, such as M.9 and M.26 can be picked from ground level. However more vigorous apple trees, on MM.106 or MM.111 rootstocks and many pear trees require short ladders to enable the pickers to reach the highest fruits on the trees.

Most pickers prefer to work on piece rates and harvesting supervisors are required to ensure that unnecessary damage is not done to fruits by over rapid and careless picking. Avoidance of bruising caused by the fruits being dropped into the picking buckets or bins is a particular problem. Damage from finger nails to the surface of the fruits is also a consideration, as is damage to the spurs of the trees or the fruits by incorrect removal of the fruits. It is important to remove the fruit with its stalk intact but with the fruiting spur remaining undamaged on the tree.

3.2 Economics of harvesting

As yields vary from season to season in UK conditions, most figures for the costs of harvesting are now quoted in pence per lb picked. In recent studies/surveys conducted on apple trees bearing average UK yields, a cost of 1.5 pence per lb (3.3 pence/kg) have been estimated. This is for a crop of approximately 18 tonnes /ha. In addition growers need to allow for a further 1.16 pence /lb for the hire and depreciation on the bulk bins.

This compares with an estimate of a further 2.5 pence per lb for growing costs (to include the costs of sprays/spraying, fertilisers, pruning and thinning). But this estimate was made when thinning costs were much cheaper due to the availability of carbaryl.

These values, although a significant component of the variable costs of production, are relatively small in comparison with the total break even cost per lb of approximately 25 pence. The table below (courtesy of Knight Tustian) shows a breakdown of these cost components and the importance of costs associated with overheads and storage/grading/marketing.:

Overhead costs	3.33 pence/lb
Growing costs (to include pruning sprays /spraying and fertilisers)	2.50 pence/lb
Harvesting	1.52 pence/lb
Orchard depreciation costs	3.01 pence/lb
Bin hire/depreciation:	1.16 pence/lb
Storage costs ((example only)	1.94 pence/lb
Grading costs	3.07 " "
Packing materials	3.50 " "
Levies and PR	0.75 " "
Transport to Market	2.00 " "
Marketing commission	1.50 " "

Increasing yields per acre or hectare should reduce slightly the costs per lb (kg) by providing the pickers with more fruits close at hand, so facilitating increased speed of picking and requiring them to walk shorter distances to bins (if correctly positioned).

The importance of large fruit size and high percentage grade outs of fruits

Small fruits are most unprofitable and no grower of apples and pears for the fresh market can expect to stay in business if a significant proportion of the crop is in grades unacceptable to the markets. This is an important consideration when considering methods of mechanical harvesting which may result in increased bruising and reduced Class I percentage grade out.

Recent estimates prepared by Knight Tustian show that, for Cox crops of approximately 10 tonnes per acre, the break even costs per lb are approximately 29 pence if 100% of the crop in the top grades. However, this breakeven cost increases to 42 pence if only 60% of the crop is in this top grade. Similar figures for a Bramley crop are 26 pence and 35 pence for 100% and 60% Class I respectively.

In a separate study undertaken by ADAS in 1995/96 the costs per acre and per hectare for harvesting were estimated to be £360 and £890 respectively. These figures were for an average yield and included regular labour, casual labour, transport from the orchard, bin hire/depreciation and other non-itemised harvesting costs.

Work in New Zealand and Ohio, USA has shown that for every 1% increase in bruising grading costs increased by up to 1.5 pence for every 40lb carton of fruits. This is addition to loss of revenue on the downgraded fruits. The importance of minimising bruising in the harvesting operations are well described in this work (Funt *et al.*, 2000)

3.3 Strategies Attempted in the UK and Abroad to Reduce the Costs of Harvesting

3.3.1 Trees of reduced stature

UK growers now grow the majority of their trees on dwarfing rootstocks, so reducing the need for ladders when harvesting. There is a good range of dwarfing rootstocks available for apple trees grown under conventional systems, although some improvements may be needed if organic systems of production continue to expand. In the future, improved dwarfing rootstocks could also help improve yields of quality fruits and also provide resistance to soil borne diseases.

Only a few dwarfing rootstocks are available for pears and none of these are as dwarfing as M.27 and M.9 used in apple culture. Breeding of pear rootstocks continues in attempts to further reduce the stature of pear trees.

3.3.2 Aids to hand picking

A simple aid to harvesting was reported by McMechan (1974) in which pickers placed or threw apples onto a catching frame. This device did not increase efficiency but it was said to reduce fatigue. However, slightly more bruising resulted and this is unlikely to be acceptable in the current market. Peterson *et al* (1997) has conducted more recent work on a similar principle, but used a more sophisticated catching mechanism. Their self-propelled machine operated on inclined trellised canopies and was operated by two seated pickers who threw or placed fruit onto a cushioned cross-conveyor. That conveyor discharged into a bin filling mechanism designed to minimise fruit damage. Productivity improvements of between 36 and 44% were claimed, though conventional harvesting yielded a higher percentage of top grade fruit (by between 2 and 12%). This suggests that despite the precautions some damage was occurring, which in the UK market would significantly reduce the productivity benefits.

Other literature on hand harvesting aids has been dominated by trials of the Dutch Pluk-O-Trac system (www.munckhof.com) that has undergone a number of developments over the last twenty years. This system attempts to improve efficiency by using conveniently placed conveyors to take apples away to bulk bins avoiding the unproductive time emptying buckets. The conveying systems are designed to reduce damage by minimising drops and using soft surfaces during the bin filling process. Went (1975) working in Germany and Anderson (1977) working in Canada both reported harvesting efficiency increases of about 20% using the Pluk-O-Trac system, though the importance of growing the orchard on a layout to suit the machine was stressed. These machines were based on twin conveyors one either side of the inter-row path and fed by two pickers each. Subsequent machinery developments included a larger unit with four finger conveyors passing into relatively narrow inter-row path and feeding a transfer conveyor over the trees and feeding a bulk bin in a wider pathway (Anon, 1981). A more recent study by Hogeschool and Bosch (1995) has found that the benefits of such picking aids are less clear cut and could vary greatly with circumstances.

One of the reasons that hand harvesting aids do not always perform as well as might be expected is that machines require a number of pickers to work at a very similar rate. Inevitably this means working at the rate of the slowest worker at any one time with an obvious loss of productivity. Much of that variation between work rates will not be caused by differences in the pickers themselves but will be due to local variation in fruit density, which are difficult to eliminate. Devising harvesting aids with provision for some fore and aft float in worker position can accommodate some of the short-term variations and can reduce the work rate penalty. Indeed the Pluk-O-Trak conveyor system does offer limited flexibility in this way. Tillett (1989) has studied this effect in the context of selective cauliflower harvesting, but the principles are relevant to the apple and pear harvest process.

3.3.3 *Mechanical harvesting*

Three categories of mechanised harvesting are to be found in the literature. Of these by far the most common are shakers. Shakers have been under development for a number of years and have been used successfully in a variety of crops. Indeed Florida citrus producers faced with increased labour costs have only recently embarked on a new industry funded shaker harvester research programme (www.fdocitrus.com). With the exception of some processing apples that can tolerate damage, such as cider apples, apple trees are often trained into a V or T shaped forms for shaker harvesters. This allows cushioned catching devices to be accommodated close to the fruit, minimising drop distance. The aim of the shaking mechanism is to vibrate the fruit at close to its natural frequency such that an oscillation is set up and its stalk breaks. The usual mechanism for achieving this is by attaching an impact shaker to the trunk and relying on the tree branch structure to transmit the vibration to the fruit (Werken, 1981, and Peterson and Miller, 1989). This works relatively well in older larger trees, but is less effective in younger smaller trees with more slender trunks and branches. To solve this problem some harvesters have attempted to transmit vibration via oscillating bars that connect with horizontal or inclined branches. An example of this called 'Trelpik' (Gould *et al.*, 1986) proved quite successful in harvesting plums and was also adequate in harvesting canning peaches, although some damage was noted on harvested fruits of this crop. Interestingly, machine harvested Williams pears showed less damage than hand picked fruit. However, although 89% removal of 'Granny Smith' apples was achieved with the machine, the fruit suffered much minor bruising (van den Ende *et al*, 1987). The 'Trelpik' harvester operated on the Australian Tatura Trellis system, for which other prototype mechanical harvesters have also been developed (van Heek and Adem, 1980; Godley, 1982).

Another approach to shaking less robust trees is the spike drum type shaker. These impart vibration via spikes that penetrate the canopy (Gyuro *et al*, 1981). By rotating the drum in line with forward speed tree damage is minimised. As the spikes contact fruit bearing branches vibration is transmitted more directly and lower intensities are required, which should reduce tree damage. However, all these techniques suffer from a number of problems. Fruit removal rates are often lower than would be achieved by hand picking, typically 90% though this is variable. Fruit damage is almost always significantly higher than hand picking despite strenuous efforts made to reduce damage in catching mechanisms. For this reason mechanised harvesting based on shaking systems is thought not to offer a solution to fresh market apple and pear production in the UK, despite the undoubted productivity benefits.

A second approach to mechanised harvesting used foam covered fingers that combed through a canopy trained in the form of a hedge (Child and LeFlufy, 1980). This approach also left significant fruit unharvested and resulted it significant damage with as many as 35% of fruit in some trials receiving bruising. There was also a problem in transferring fruit from the comb onto the elevating conveyor.

The third approach utilised a rod press designed to remove fruit from a Lincoln canopy T-trellis. The rod press consisted of an array of rubber or silicon tipped rods at a 50mm pitch. This array was held over the horizontal canopy and slowly pushed down dislodging fruit into a container held below. Each rod was held in place by a spring-loaded ball that would yield if the vertical force exceeded 34N, a figure adequate to cause fruit removal, but low enough to avoid serious tree damage. A field evaluation of this experimental technique gave fruit removal rates of between 88 and 98% with typically 80% of fruit in the top grade. This was comparable with a shaker harvester evaluated at the same time (Peterson and Miller, 1989).

3.3.4 Robotic harvesting

Advances in industrial robotics during the 1980's encouraged a number of research groups to investigate the possibilities of harvesting apples using robots. It rapidly became clear that the natural variability of the orchard environment introduced a number of difficult new challenges. Two groups in particular took up the challenges and progressed to experimental systems capable of operating in commercial orchards. One, MAGALI was started by a team at CEMAGREF in France (Grand D'Esnon et al, 1987 and Bourely et al, 1990) and was further developed in a French/Spanish collaboration (Eureka Project No EU 176 CITRUS) to operate in orange groves (Frachard, 1992). A second system was developed in the USA concentrated initially on citrus (Munilla, 1986). This project was also continued as an international collaboration. This time with Hungary and the focus switched to apples (Kassay, 1997).

Although there were significant technical differences in approach between the two teams they both had the same basic format. That was computer analysis of video images to detect fruit and a three-degree of freedom manipulator (arm) to position an end-effector (hand) to detach the fruit. Both also attempted to improve the economics of operation by mounting multiple robot arms on a single harvesting platform. Both systems overcame many of the technical challenges, but some problems remained. Despite very considerable research effort and the close involvement of industrial partners, both projects have to date failed to achieve commercial success.

3.4 Future Strategies considered worthy of further investigation

From the perspective of fruit for the fresh market there would seem to be little point in investing significant resources into mechanised harvesting systems. Despite considerable research effort damage levels remain higher than hand harvested fruit and as discussed earlier this is likely to be commercially unacceptable.

Robotic harvesting, whilst having the potential to deliver a higher quality product, is still more expensive than harvesting by hand. It seems likely that as technology becomes less expensive, and labour costs continue to rise there will come a point at which robot harvesting is cost effective. However, that time has not yet come and the cost of continuing the research coupled with the high capital cost of any commercial equipment are unlikely to provide short or medium term solutions to the UK industry.

Hand harvesting aids have proved to be commercially successful in some cases, though the evidence suggests that their viability is dependent on circumstances. Use of existing commercial devices would seem worthy of consideration on a grower by grower basis.

If growers are to maintain their existing harvesting systems relatively unchanged then the most beneficial area for development may lie in developing tree varieties, training techniques or pruning strategies to make hand harvesting ergonomically more efficient. The principal concerns might be to bring fruit down to a height that does not require ladders, keeping fruit visible and within reach without undue stretching.

4. Discussion

Adoption of alternative/new systems of pruning/training

One possible strategy which may warrant consideration in the future is the adoption of alternative systems of pruning and training aimed at reducing the costs of pruning, thinning and harvesting either by increasing the efficiency of conventional practices or by being amenable to mechanisation.

The V system of training adopted by some growers in Victoria, Australia (the Tatura trellis system) was developed with these objectives in mind. The advantages cited for the system are a) it fills its allotted space quickly, b) it produces uniform and controlled distribution of leaves and fruit, so improving light interception and photosynthetic efficiency, c) it produces an ordered branch and leaf array that diminishes light competition within and between trees, so minimising the effects of crowding that usually result from high plant densities, d) it facilitates close planting that creates root competition, thereby reducing vegetative vigour and increasing fruitfulness and e) it accommodates large numbers of trees / ha so inducing high yields early in the orchard's life.

The designers of the Tatura trellis also believed that the system should be much easier to mechanise than conventional systems of pruning/training. The planar positioning of the surfaces of the branches allows easy positioning of machines and aids. Also the system allows machines to operate beneath the branches to facilitate the recovery of fruits during harvesting and the shallow branch system avoids excessive damage to fruits as they fall from the limb to the catcher. This shallow branch canopy also facilitates good spray penetration. Over the row summer pruning is also possible.

This and similar systems have been used quite extensively in Italy, Holland and Belgium for the cultivation of pears. However, with the recent loss of the growth regulator CCC, growers are now experiencing great problems in controlling the vigour of these trees, which are planted very closely together on rootstocks that are insufficiently dwarfing. This was rarely a problem in the early trials conducted in Australia, because there the soils were shallow and growth was controlled very effectively by techniques of regulated deficit irrigation. In areas where soils are deeper and rainfall more abundant dwarfing rootstocks will be essential to control the growth of trees on this system.

The other major problem with the Tatura trellis system is that estimates suggest that it can cost approximately twice as much as a traditional system based on widely spaced trees grown in conventional shapes to bring trees into bearing (Jotic, 1983; Stebbins, 1985). This is a common problem associated with all intensive systems.

Adoption of new machinery based approaches to labour reduction

Harvesting

In reviewing past attempts to reduce labour it is clear that considerable effort has already gone into improving the harvesting process. For the fresh market history would suggest that the largest benefits have come from the use of simple tools such as picking buckets in conjunction with the development of orchard layouts that provide an ergonomic workplace. Whilst technology has continued to develop, its relative lack of commercial success would suggest, that from the perspective of a UK industry, large investment in sophisticated harvesting technology would be an unwarranted risk. Further investment in improving orchard layout would seem to offer the best short to medium term strategy to improving productivity.

Pruning
Mechanical pruning has also received significant research attention, though much of this has been targeted at novel canopy structures that are not widely used in the UK. Comparatively little work seems to have been done on relatively low technology approaches to reducing manual pruning through an initial mechanised pass. This would seem worthy of further investigation, as the potential cost savings are significant and the relatively long season means that equipment can be justified over a relatively large area. Some of the technical issues are:

- Quality of the cut required from a plant health perspective
- Cutting mechanisms for achieving that quality at an acceptable work rate
- Cutter bar tractor mounting arrangements to facilitate accurate profiling of trees at relatively high speeds
- Establishment of the feasibility of deploying horizontal cutter bars under operator control within the canopy to further reduce subsequent manual pruning
- Conduct a detailed investigation into the likely impact of semi-mechanised pruning on labour and product quality/yield to establish cost benefit

Thinning
Mechanised thinning has received relatively little attention as the problem has until recently been adequately solved by chemical means. Consequently there is probably more scope for new technical solutions that may have a big impact. The problem is also of particular importance, as it will require high levels of labour input at a time when traditional seasonal labour is not available. The relatively critical timing of the operation will make the labour availability issue all the more significant, but has the disadvantage that any equipment will have a very short operating season. We would suggest that a number of relatively simple trials could be conducted in the first instance to establish the feasibility of some of the techniques discussed in this report.

In the context of water jet thinning these could be conducted with a small number of lances equipped with a variety of nozzles and supplied from a pump whose output pressure could be regulated. Key issues to investigate would include:

- Minimum pressure/flow rate required to prevent fruit set in blossom
- Maximum pressure/flow rate before leaves/tree is damaged
- Range of operation
- Effect on quality of fruit
- Number and spacing of nozzles required to provide adequate coverage
- Need or otherwise for spatially selective blossom targeting and at what scale

Similarly thinning using hot air could be investigated using a hand held device from which the flow rate and temperature could be regulated. The key issues in this case might be:

- Minimum temperature/flow rate required to prevent fruit set in blossom
- Maximum temperature/flow rate before leaves/tree is damaged
- Range of operation
- Effect on quality of fruit

If the results of these initial trials were promising prototype equipment could be constructed for farm scale tests, possibly in a direct comparison to existing commercial alternatives such as the Gessler strimmer.

5. Conclusions

Mechanised alternatives to hand thinning offer the most scope for labour saving in UK apple and pear production in the short/medium term. The availability until now of chemical thinners has meant little development has taken place, thus providing scope for innovation. Candidate techniques for blossom thinning that we consider worthy of consideration are:

- Strimming (e.g. Gessler machine)
- High pressure water
- Hot air

Shaking is the only viable technique for mechanised thinning of fruitlets of which we are aware. Due to the dominance of slender spindle orchards in the UK we would suggest that spiked drum shakers offer the best prospect.

Whilst a combination of mechanised blossom and fruitlet thinning might offer the best longer term prospect we would recommend concentrating on blossom thinning in the first instance. We believe that the development costs will be lower and that in the short term mechanised blossom thinning could be combined with limited hand fruitlet thinning.

Mechanised pruning would seem to offer the second most promising area for labour reduction. We consider that strategies based on cutter bars to externally shape trees combined with hand pruning offer the best short-term prospects. We feel that not enough is known about the consequences of cut quality achieved by existing cutter bar systems and that some investigation should take place. We feel that there is technical scope for new cutter bar mechanisms to improve cut quality and workrate.

Should mechanised external shaping prove successful we believe it may also be possible to provide some mechanised pruning within the tree structure.

We are not optimistic about the short to medium term prospects for mechanical harvesting of fresh market produce in UK orchards. Robotic technology is too expensive and technically not sufficiently advanced. Other mechanised techniques would rely on an expensive change to trellis based training systems and would not necessarily offer the quality of product demanded by the UK fresh market.

We believe that there may be some benefit in growers considering the commercially available harvesting aids against their own specific situations. Developments in the use of dwarfing rootstocks to bring tree height down and avoid the use of ladders would be of particular benefit in pears.

6. References

Anderson, E.T. and Hutchinson, A. (1977) High density apple orchard studies in Ontario and experience with Pluk-O-Trak harvesting aid. Proceedings of the New York State Horticultural Society. 122: 89-95.

Anon. (1981) Harvesting with vertical picking bands. Fruitteelt, 71:49, 1402-1403. (In Dutch)

Anon (1995) Braeburn: hortipratic. Centre technique interprofessionnel des fruits et legumes (C.t.i.f.l) Paris France, 52pp.

Anon (1995) Gala: hortipratic. Centre technique interprofessionnel des fruits et legumes (C.t.i.f.l) Paris France, 63pp.

Barritt, B.H. (1992) Intensive orchard management Good Fruit Grower, Yakima, Washington, USA 211pp.

Baugher, T.A., Elliott, K.C., Leach, D.W., Horton, B.D. and Miller, S. 1991. Improved methods of mechanically thinning peaches at full bloom. Journal of the American Society for Horticultural Science, 116: 766-769.

Bourely, A., Rabatel, G., Grand D'Esnon, A. and Sevila, F. (1990) Fruit harvesting robotization. Ten years of CEMAGREF experience on apple, grape and orange. Ag Eng 90. 24-26th October, Berlin.

Bound, S.A. and Jones, K.M. 1997. investigating the efficacy of endothal as a thinner for red 'Delicious' apple. Journal of Horticultural Science, 72: 171-177.

Bound, S.A., Jones, K.M., Koen T.B. and Oakford, M.J. (1991) The thinning effectr of benzyladenine on red 'Fuji' apple trees. Journal of Horticultural Science, 66: 789-94.

Brown, G.K. and Kollar, G. 1996. Harvesting and handling sour and sweet cherries for processing. IN Cherries: Crop Physiology, Production and Uses (editors A.D. Webster and N.E. Looney) CAB International , Uk. 443-470.

Brunner, T. (1990) Physiological fruit tree training for intensive growing. Akademiai Kiado, Budapest, Hungary ; 286pp.

Byers, R.E. 1989. High pressure water stream bloom thinning and GA3 sprays on flower bud numbers and distribution in peach trees. Annual Report of the State Horticultural Society, Michigan, USA, 119.

Ferree, D.C. (1989) Influence of orchard management systems on spur quality, light and fruit within the canopy of 'Golden delicious' apple trees. Journal of the American Society for Horticultural Science, 114: 869-75.

Ferree, D.C. 1996. Performance of benzyladenine as a chemical thinner on eight apple cultivars. Journal of Tree fruit Production, 1: 33-50.

Fitch, L.B. 1981. Factors affecting fruit growth and quality In Prune Orchard Management, Division of Agricultural Sciences, University of California Special Publication 3269, 60-64.

Fitch, L.B., Ramos, D.E. and Yeager, J. 1972. Tree shaker thinning of French prunes. Californian Agriculture, 26: 5-6.

Forshey, C.G., Elfving, D.C. and Stebbins, R.L. (1997). Training and pruning if apple and pear trees. Alexandria, Virginia, USA. American Society of Horticultural Science.

Frachard, O. (1992) De MAGALI à citrus ou de la pomme à l'orange. L'Arboriculture Fruitiere. No 454, Octobre 1992. (In French)

Funt, R.C., Cameron, E.A. and Banks, N.H. 2000. The effect of apple fruit bruising on total returns. Goodfruit Grower, 51: (14) 37-40.

Glenn, D.M., Peterson, D.L., Giovannini, D., Faust, M. (1994) Mechanical thinning of peaches is effective postbloom. Hortscience, 29:8, 850-853.

Godley, G.L. 1982. Mechanical harvesting in Australia is moving. Apple and Pear World, 2: (2) 8-9.

Gould, I.V., Young, G.S. and Godley, G.L. 1986. Mechanised fruitharvesting from the Tatura Trellis. American Society of Agricultural Engineers Paper 86: 1070.

Grand D'Esnon, A., Rabatel, G., Pellenc, R., Journeau, A. and Aldon, M.J. (1987) MAGALI: A self-propelled robot to pick apples. American Society of Agricultural Engineers, Summer Meeting, Baltimore, June 28th-July 1st, Paper No 87-1037.

Grauslund, J. 1980. Fruit thinning V. Experiments with chemical and mechanical thinning of plums. Tidsskrift for Planteavl, 84: 519-529.

Greene, D.W., Autio, W.R. and Miller, P. 1990, Thinning activity of benzyladenine on several apple cultivars. Journal of the American Society for Horticultural Science, 115: 394-400.

Guarella, P. (1972) Trials on mechanized pruning of pear and peach trees. Annali della Facoltta di Agraria, Universita di Bari. 25: 405-424. (In Italian)

Gyuro, F., Velich, S., Geizler, J. and Sipos, B. (1981) The apple curtain system for mechanisation. Acta Horticulturae. No114, 255-260.

Hogeschool, A. and Bosch, D. (1995) Harvesting performances of different methods of harvesting scarcely differ. Fruitteelt (Den Haag), 85:27, 18-19. (In Dutch)

Jackson, D.I. and Looney N.E. (1999) Temperate and subtropical fruit production 2nd edition CABI Publishing Wallingford UK332 pp.

Jotic, P. 1983. Establishment costs of semi-intensive and intensive orchards. Dept. Agr. Tasmania Workshop Paper 40.

Kassay, L. (1997) Results of research of the AUFO 12/9 armed fruit picking robot. American Society of Agricultural Engineers, Summer Meeting, Minneapolis, August 8th-12th, Paper No 973094.

Kelderer, M., Strimmer, M., Casera, C. and Lardschneider, E. (1998) First experiments on thinning apples grown organically. Rivista di Frutticoltura e di Ortofloricoltura. 60: 4, 61-65.

Kesner, C.D., Hansen, C.M. and Fouch, S. 1981. Tree training and mechanical pruning of tart cherry in high density planting. Compact Fruit Tree, 14: 135-139.

Kesner, C.D. and Nugent, J.E. 1984. Training and pruning young cherry trees. Michigan State Cooperative Extension Bulletin E-1744.

Lauri, P-E. and Lespinasse, J-M. (1999) Apple tree training in France: Current concepts and practical implications. Fruits 54: 441-449.

Lauri, P-E. and Lespinasse, J-M. (2001) Genotype of apple trees affects growth and fruiting responses to shoot bending at various times of the year. Journal of the American Society for Horticultural Science, 126: 169-174.

Lespinasse J.-M and Delort, F. (1986) Apple tree management in vertical axis: appraisal after 10 years of experiments. Acta Horticulturae, 160: 120-155.

Lisa, L. (1996) The mechanisation of some piedmont operations in vine-growing- Part II. Articolo. 3. 14-16. (In English and Italian)

McFarlane, N.J.B. ,Tisseyre, B., Sinfort, C., Tillett, R.D., Sevila, F. (1997) Image analysis for pruning of long wood grape vines. Journal of Agricultural Engineering Research. 66, 11-119.

McMechan, A.D. (1974) New apple harvester calls for pick and toss. British Columbia Orchardist. 14: 11, 14-15.

Menzies, A.R., (1980) Timing, selectivity and varietal response to mechanical thinning of apples and pears. Journal of Horticultural Science. 55:2. 127-131.

Mercurio, J.F., Gunkel, W.W., Sobel, T.A. (1989) Vision-guided block-type robotic grapevine pruner. American Society of Agricultural Engineers, Winter Meeting, New Orleans, December 12-15, Paper No 89-7519.

Munilla, R.D. and Harrell, R.C. (1986) Flexible manipulator control for a fruit harvesting robot. American Society of Agricultural Engineers, Winter Meeting, Chicargo, December 16-19, Paper No 86-1554.

Mika, A. (1992) trends in fruit tree training and pruning systems in Europe. Acta Horticulturae, 322: 29-35.

Neuteboom, D. and Withnall, M. (1998) Cox at its best – the whole story. 152pp. ISBN No 0-9531850-0-2

Perry, R., Swinton, S. and Schwallier, P. 1997. Labor requirements for 'Empire' and 'Jonagold' affected by rootstock and three orchard systems in the Michigan NC 140 trial. Acta Horticulturae, No 451: 459-465.

Peterson, D.L., Miller, S.S. (1989) Advances in mechanical harvesting of fresh market quality apples. Journal of Agricultural Engineering 42, 43-50.

Peterson, D.L., Miller, S.S. and Wolford, S.D. (1997) Apple harvest aid for inclined trellised canopies. Transactions of the ASAE. 40: 3, 529-534.

Peterson, D. L., Takeda, F., Kornecki, T.S. (1989) New shaking concept for brambles.Trans. Amer. Soc. Agr. Eng. 32(4):1165-1168.

Powell, A.A., Hancock, B.G., Puls, E.E. (1976) Facing labour problems? Mechanical thinning can help. American fruit grower. 96: 1, 18, 28-30.

Predieri, S. 1998 Compact pears obtained through *in vitro* mutagenesis. Acta Horticulturae, 475: 93-98

Predieri and Govoni, M. 1998 *In vitro* propagation of compact pear clones. Acta Horticulturae, 475: 127-132.

Quamme, H.A., Brownlee, R.T. and Kappel, F. 1997. Evaluation of five apple training systems in the Okanagan valley of British Columbia. Acta Horticulaturae, 451: 495-504.

Robinson, T.L. and Lakso, A.N. (1991) Bases of yield production efficiency in apple orchard systems. Journal of the American Society for Horticultural Science, 116: 188-194.

Robinson, T.L., Wunche, J. and Lakso, A. (1993) The influence of orchard system and pruning severity on yield, light interception, conversion efficiency, partitioning index and leaf area index. Acta Horticulturae, 349: 123-127.

Schroder, M. and Link, H. (1996) Date of use of a thinning machine. Schweizerische Zeitschrift Fuer Obst und Weinbau, 132:23,613. (In German)

Sevila, F., Baylou, P., Piquet, J.C. (1990) Computer vision systems and growth modelization softwares applied to grapevine woods as pruning robots design and control tools. Ag Eng 90, Berlin 24-26th October, Paper No 1014.

Stebbins, R.A. 1985. Comparison of orchard designs (systems). Goodfruit Grower, 36 (9) 12-15.

Szelevenyi, A. 1974. Gyumolczritkitas razogeppel Balutongoglaren [Fruit thinning with a shaking machine at Balaton-boglar], Kerteszetes Szoleszet, 25:5.

Tillett, N.D. (1989) A simulation analysis of alternative methods of hand harvesting cauliflower. Journal of Agricultural Engineering Research 42, 179-192.

Tillett, N.D., Hague, T., Marchant, J.A. (1998) A robotic system for plant scale husbandry. Journal of Agricultural Engineering Research, 69, 169-178.

Van den Ende, D., Chalmers, D.J. and Jerie, P.H. (1987) Latest developments in training and management of fruit crops on Tatura trellis. HortScience, 22: 561-568.

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Van Heek, L.A.G. and Adem, H.H. (1980) Mechanical harvesting of Tatura trellis fruit trees. Journal of the American Society for Horticultural Science, 105: 695-699.

Webster, A.D. 1993. Tree growth control and fruit thinning; possible alternatives to the use of plant growth regulators. Acta Horticulturae, 347: 149-161.

Webster, A.D., Atkinson, C.J., Lucas, A.S., Vaughan, S.P. and Taylor, L. 2000 Interactions between root restriction, irrigation and rootstock treatments on the growth and cropping of 'Queen Cox' apple trees: Effects on orchard growth and cropping. Journal of Horticultural Science, 75: 181-189.

Webster, A.D. and Spencer, J.E. 1999. New strategies for the chemical thinning of apple (*Malus domestica* Borkh.) cultivars Queen Cox and Royal Gala. Journal of Horticultural Science and Biotechnology, 74: 337-346.

Went, T. (1975) Apple harvesting into bulk bins with the Pluk-O-Trak. Erwerbsobstbau. 17: 7, 100-103. (In German)

Werken, J.v.d. (1981) Possibilities of harvest mechanisation in high density planting hedgerow systems. Acta Horticulturae. No114, 221-231.

Wertheim, S.J. (1970) the training of the slender spindle of four apple varieties. Proefstation voor de Fruitteelt, Wilhelminadorp, The Netherlands Publication No. 10 : 158pp.

Wertheim, S.J. (1980) High density planting: development and current achievements in the Netherlands, Belgium and West Germany. Acta Horticulturae, 114: 318-327.

Wertheim, S.J. (1990) De peer. Mededeling nr 22, Proefstation voor de Fruiteelt, Wilhelminadorp, the Netherlands 338pp

Williams, M.W. 1993. Sulfcarbamide, a blossom thinning agent for apples. HortTechnology, 3: 322-4.

Williams, M.W. 1994. Factors influencing chemical thinning and update on new chemical thinning agents. Compact Fruit Tree, 27: 115-122.

Williams, M.W., Bound, S.A., Hughes, J. and Tustin, S. 195. Endothall: a blossom thinner for apples. Hort Technology, 5: 257-9

Williams, R.R. (19??) Cider and juice apples: Growing and processing. University of Bristol Printing Unit, 123pp.

Woodward, P.J. 1971. Plum: Mechanical thinning. Luddington Experimental Station Annual Report for 1970. 33, 35-37.

Worraker, R. and Withnall, M. (1997) Royal Gala in England. Malcolm Withnall Hollingbourne, Kent, UK 112pp.

Young, G.S. and Jerie, P.H. 1984. A cutter bar for summer pruning Tatura Trellis fruit trees. Agr. Eng Austral. 13: 19-23.

Zocca, A. (1980) Mechanisation in palmette fruit orchards. Centro di Studio per la Tecnica Frutticola, CNR, Bologna. Publicazione No 144, 40pp. (In Italian)