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| **Project title:** | Developing water- and fertiliser-saving strategies to improve fruit quality and sustainability of irrigated high-intensity, modern and traditional pear production |
| **Project number:** | TF 198 |
| **Project leader:** | Dr Mark A. Else, East Malling Research |
| **Report:** | Final Report, March 2013 |
| **Previous report:** | Annual Report 2012 |
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| **Location of project:** | East Malling Research<br>New Road, East Malling, Kent, ME19 6BJ |
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| **Date project commenced:** | 1 April 2011 |
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## AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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**Contents**

# GROWER SUMMARY

## Headlines

Irrigation Test Regimes applied in the Concept Pear Orchard at EMR delivered water savings of between 62 and 85%, compared to the commercial controls and class 1 yields and fruit quality were maintained or improved.

## Background and expected deliverables

Irrigation is essential for the successful establishment and continued productivity of high-intensity tree fruit growing systems. Modern and traditional orchards also rely increasingly on irrigation to deliver the yields and quality needed for a profitable business. More efficient use of inputs, including labour, water and fertilisers, is vital to the future success of the industry. Seventy six per cent of tree fruit growers farm in areas where water resources have already been classified by the Environment Agency (EA) as under increasing stress and abstraction rates in these areas are currently unsustainable. Recent droughts, particularly affecting the southeast, east and midlands regions (Figure 1), have highlighted the need for growers to use water (and fertilisers) more efficiently.


**Figure 1** Assessment of drought risk across England and Wales for 2012. Source: Environment Agency

Projected increases in agricultural water demand in the 2050s in England and Wales range from 25% to 180% of current demand (EA, 2008). One useful indicator of aridity that is widely used is the potential soil moisture deficit (PSMD), which represents the balance between rainfall and potential crop water use over the year. It is estimated that in the southeast the average annual maximum PSMDs that currently occur every five years will occur every two years by 2080 and deficits that currently occur every 15 years will occur every five years by 2080. Therefore, there will be an increasing reliance on irrigation to ensure profitable tree fruit production.

Trickle/drip irrigators have so far been exempt from legislation designed to safeguard resources and limit damage to the environment (e.g. Water Framework Directive 2000, Water Act 2003). However, Defra and the Welsh Government are working with the Environment Agency and Ofwat on a project to reform the water abstraction licensing system (http://www.defra.gov.uk/abstraction-reform/). It is envisaged that all drip irrigators will require an abstraction licence in future and growers must be able to demonstrate an efficient use of available water before time-limited abstraction licences are renewed.

If tree fruit growers are to maintain or increase yields against a backdrop of increasing summer temperatures, dwindling water supplies, and governmental demands for greater environmental protection, new production methods that improve water and nutrient use efficiency and utilise 'best practice' are needed. However, there are few guidelines for growers on how best to schedule irrigation, and matching demand with supply can be difficult in changeable summer weather and at different stages of crop development. The aim of TF 198 was to develop irrigation scheduling regimes for intensive pear orchards that optimise water and nutrient inputs and minimise run-through past the rooting zone, without reducing Class 1 yields or quality.

Current best practice irrigation recommendations for Conference pear are to maintain soil matric potential within the rooting zone between field capacity (approximately -10 kPa) and -30 kPa during flowering and for up to six weeks after petal fall. Soil is then allowed to dry to -60 kPa between irrigation events until early July before irrigation is withheld to encourage the cessation of extension growth and set of the terminal bud. During the latter half of July and during August, irrigation should then be scheduled to maintain soil matric potenntial between -10 and -25 kPa. These guidelines were developed overseas and, although they provide a useful starting point, new guidelines are needed for use by UK tree fruit growers to ensure that high yields of quality fruit with good shelf-life potential can be produced in an environmentally sustainable way. This is especially important for the UK tree fruit industry, since the major areas of production are in regions where pressure on limited water supplies is increasing. The scientific underpinning work needed to develop improved irrigation best practice guidelines is being carried out in this project. All experiments were carried out in the Chingford's Concept Pear Orchard (CPO) at EMR.

Expected deliverables are:

- Irrigation guidelines to optimise water use efficiency in modern and high-intensity growing systems on a range of soil types used for fruit growing in the UK.
- Improved understanding of how to manage irrigation to set the terminal bud without affecting yields or quality.
- Increased awareness of the effects of scheduled versus unscheduled irrigation on canopy growth and fruit quality.
- Improved sustainability of irrigated pear production.
- Demonstrable compliance with legislation (Water Framework Directive, The Water Act, The Nitrate Directive).
- Delivery of research needed to develop deficit irrigation regimes to control shoot extension and improve fruit quality and storage potential.

## Summary of the project and main conclusions

In this project, Irrigation Test Regimes (ITRs) were developed for each of the four growing systems in the CPO to try to optimise water use efficiency (WUE) without reducing Class 1 yields or quality. To optimise WUE, the frequency and duration of irrigation events must be managed carefully to avoid excessive irrigation inputs and to limit run-through of water and nutrients past the rooting zone. In order to achieve this, information on changes in soil water availability and soil moisture content at different depths within the rooting zone throughout the season is needed. In this project, Decagon MPS1 probes and Decagon 10HS probes (Figure 2) were used to measure soil water availability and soil moisture content, respectively. Additional data on soil moisture content was provided by Sentek 'EnviroScan' multi-depth capacitance probes.


**Figure 2.** Decagon MPS1 probes and 10HS probes used to measure soil water availability and soil moisture content in the concept pear orchard at EMR

### *Experimental design*

Four experiments were set up in the Concept Pear Orchard (CPO), one for each of the growing systems, with two irrigation treatments per experiment. The two irrigation treatments were:

- Commercial Regime (CR), in which the frequency and duration of irrigation events was decided by Graham Caspell, EML's farm manager;
- Irrigation Test Regime (ITR), in which irrigation was scheduled once soil water availability reached a pre-determined value (soil matric potential - see below).

Within each growing system, three central rows each containing 28 trees were selected for inclusion in the experiment. Each row was an experimental block. Half of the trees within each block received the CR and half the ITR. The ITR was imposed by installing a separate irrigation line to 14 trees in the middle of each of the three rows and irrigation to these plots was controlled using Galcon irrigation controllers in each of the four growing systems. To the north and south of the 14 ITR trees, seven trees receiving the CR were included in the block. Within each experimental block, two CC and two ITR trees were selected on which all physiological and fruit yield/quality measurements were conducted; there were six replicate trees per treatment in each experiment.

### *Scientific approach*

The approach used in this project was to impose temporary and gradual soil drying so that the soil matric potential (water availability) within the rooting zone at which tree physiology is first affected could be identified. This information can then be used to set the lower irrigation set point for each growing system. Since the aim of this work was to develop a 'low-risk' strategy for commercial growers, the lower irrigation set point was set 70 kPa above the value (soil matric potentials are negative values) at which physiological responses were first detected. Additional Decagon 10HS probes and multi-depth capacitance probes that measure volumetric soil moisture content were also inserted within and below the rooting zone to help to inform the development of the ITRs.

### *Irrigation to the commercial trees*

The frequency and duration of irrigation events under the CR (and the majority of the CPO) were decided by Mr Graham Caspell (EML's farm manager) with advice from Mr Henk Nooteboom (Verbeek Boomkwekerijen B.V.). Irrigation was applied for 30 min daily *via* 1.6 L $h^{-1}$ emitters spaced 50 cm apart from white bud (13 April 2012) until 11 August 2012, when irrigation was withheld temporarily to terminate extension growth and encourage the terminal bud to set. Irrigation was then applied for 1 h each day from 21 August. On 30

August, irrigation time increased by 30 min until harvest on 16 September 2012 to avoid drought stress. After harvest, all trees were un-irrigated throughout autumn and winter 2012-2013.

### *Irrigation Test Regimes*

Irrigation was withheld from the ITR experimental blocks from 8 July 2012 until the average soil matric potential measured at 20 and 40 cm depth within the rooting zone reached -190 kPa. The frequent rainfall over the summer meant that the soil matric potential remained near to field capacity (-11 kPa) until 23 June when the soil beneath the ITR trees began to dry (**Error! Reference source not found.**3). The soil matric potential fell to -120 kPa at the beginning of July, when prolonged heavy rainfall returned the soil to field capacity. The soil began to dry down again in mid-July and reached the target of -190 kPa on 2, 3, 4 and 13 August 2012 for the Traditional, Central leader, U -system and V-system respectively. Then, irrigation was reinstated to the ITR treatments; 2 h of irrigation was sufficient to raise the soil in the rooting zone to field capacity without overly wetting the soil. The target set point of -120 kPa was considerably lower than the -70 kPa current 'best practice' value for this stage of development and was expected to deliver significant water savings compared to current 'best practice'. Irrigation was then applied throughout July and August once the lower irrigation set point was reached (Figure 3). The duration of each subsequent irrigation event was adjusted to ensure that the soil in the rooting zone was returned to field capacity but that run-through of water and fertilisers past the rooting zone was minimised.

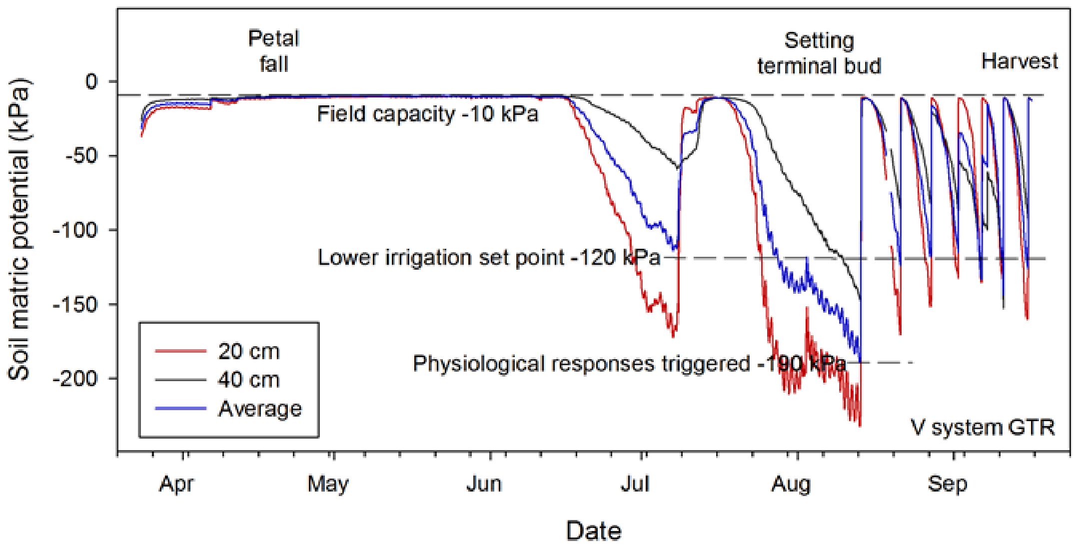



**Figure 3.** Changes in average soil matric potential (kPa) in the rooting zone of four representative trees under the irrigation test regime in the V-system. Seven irrigation events applied between 13 August and 15 September 2012.

### *Effects of the irrigation regimes on fruit growth and yields*

Fruit diameter and height were unaffected by irrigation regime in all the four systems (Figure 4). Estimates of increases in fruit volume were used to calculate daily fruit expansion rates and these were also unaffected by irrigation regime.

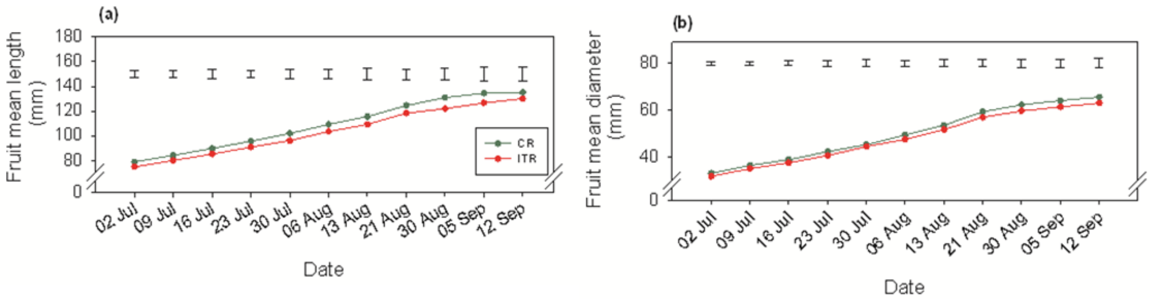



**Figure 4.** Cumulative fruit diameter (a) and height (b) over the 2012 season under the commercial (CR) and the irrigation test regime (ITR) in the V-system. Vertical bars are LSD values at $p<0.05$; there were no statistical significant differences between the irrigation treatments.

### *Fruit yields and size at harvest*

Fruit was harvested from the orchard on 16 September 2012. In each growing system, fruit from the 12 trees on which physiological and fruit growth measurements had been recorded were picked into individual crates, which were then graded into three classes, Class 1 (>50 mm diameter), Class 2 (45-50 mm diameter) and waste (fruit that were <45 mm diameter, misshapen, damaged, where rough russet was present, or deemed to be nutrient deficient, scab infected etc.). The number and fresh weight of fruit in each of these classes were recorded, and the reason for classifying individual fruit as waste was noted.

The yield and number of Class 1 fruit from each tree was not significantly different between those grown under the two irrigation regimes (Figure 5a). There were no significant differences in Class 2 yields between the ITR and CR in any growing system (Figure 5b). The mass of waste fruit (due to small size, insect damage, misshape, rots etc.) ranged between 1.6 and 3.1 kg. The average weight of individual Class 1 and Class 2 fruit at harvest did not differ significantly between irrigation regimes within a growing system (Figure 6 a and b); individual fruit weight was the lowest in the Traditional system at 180 g and highest in the V-system at 220 g. As anticipated, estimated fruit volumes at harvest mirrored the individual fruit weights noted above with the lowest volume (123 $cm^3$) in the Traditional system and the highest volume (143 $cm^3$) in the V-system.

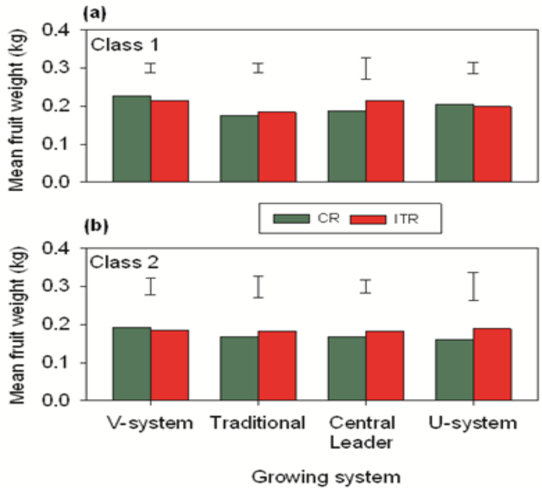



**Figure 5.** Average mass of Class 1 and Class 2 fruit per tree under the commercial (CR) and irrigation test (IRT) regimes for each growing system. Results are the average of six trees. Vertical bars are LSD values at $p<0.05$; there were no statistical significant differences between the irrigation treatments.

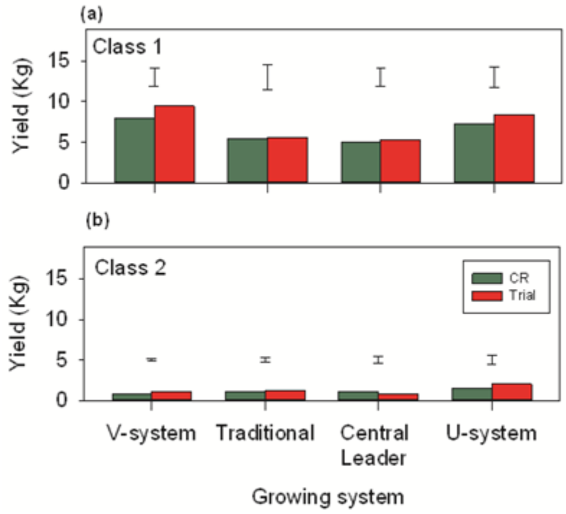



**Figure 6.** Yields of Class 1 and Class 2 fruit per tree under the commercial (CR) and irrigation test (IRT) regimes, for each growing system. Results are the average of six trees. Vertical bars are LSD values at $p<0.05$; there were no statistical significant differences between the irrigation treatments.

**Table 1.** Fruit firmness (maximum load) and soluble solids content (SSC), % smooth russet and colour parameters (L*, a* and b*) at harvest for fruit from the commercial regime (CR) and irrigation test regime (ITR) from each of the four growing systems. Values presented are the averages of 18 fruit, three from each of six replicate trees. LSD's are at p<0.05, SED=8.

| Growing system | Irrigation regime | Firmness (N) | SSc (% Brix) | Russet (%) | Colour parameter | | |
|---|---|---|---|---|---|---|---|
| | | | | | L* | a* | c* |
| V-system | CR | 61.4 | 14.5 | 60.6 | 52.4 | -5.3 | 28.7 |
| | ITR | 61.6 | 14.4 | 62.2 | 52.6 | -5.6 | 29.3 |
| | F. prob. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| | LSD | 1.92 | 0.98 | 14.5 | 1.7 | 2.2 | 1.8 |
| Traditional | CR | 64.1 | 14.0 | 60.1 | 51.2 | -5.7 | 27.3 |
| | ITR | 61.9 | 14.0 | 63.3 | 52.2 | -5.6 | 28.4 |
| | F. prob. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| | LSD | 9.29 | 0.70 | 17.3 | 1.6 | 3.1 | 2.4 |
| Central Leader | CR | 61.7 | 14.6 | 68.2 | 51.9 | -5.3 | 28.1 |
| | ITR | 61.5 | 14.9 | 55.8 | 50.6 | -5.0 | 27.0 |
| | F. prob. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| | LSD | 3.29 | 0.86 | 15.6 | 1.7 | 1.9 | 1.9 |
| U-system | CR | 63.7 | 14.1 | 54.3 | 50.9 | -6.1 | 27.2 |
| | ITR | 62.7 | 13.8 | 55.0 | 51.0 | -5.2 | 26.5 |
| | F. prob. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| | LSD | 2.19 | 0.75 | 18.5 | 1.2 | 2.0 | 1.3 |

### *Fruit quality components at harvest*

There were no significant differences between irrigation treatments in values of firmness, SSC (% Brix), percentage smooth russet or the colour parameters of fruit harvested from any of the four growing systems (Table 1). A relatively high degree of russeting was noted due to the wet conditions in 2012.

### *Irrigation volumes applied in the two regimes*

Although irrigation was applied daily to all trees from mid April 2012, the ITRs were first applied on 8 July 2012 and so the number of hours of irrigation and the resulting volumes of water applied to the ITRs from 8 July to 16 September 2012 in each of the growing systems was calculated (Table 2). In the CR irrigation was applied for 20 min daily from 1 July till 11 August 2012 before being turned off to trigger the setting of the terminal buds. Between 21 and 30 August 2012 irrigation was applied for 60 min each day, after which the daily irrigation duration was increased to 90 min until harvest on 16 September 2012. Assuming that two 1.6 L $h^{-1}$ emitters spaced 50 cm apart effectively irrigated each tree, the total volume of water applied to each tree under the CR and ITR in the four different growing systems was calculated (Table 2). Water savings of between 64 and 77% were achieved under the ITRs compared to the CRs. The volume of water applied to the four growing systems under the ITRs also varied; 45 L per tree was applied to the V-system whilst 70 L per tree was applied to the CL system (Table 2). Since trees were fertigated at each irrigation event until 30 August 2012, the total amounts of the macro and micro nutrients applied were reduced in proportion to the irrigation volume. Consequently, fertiliser savings of between 62 and 85% were achieved using the ITR. Despite these reduced inputs no visual deficiencies were observed.

**Table 2.** Total irrigation (h) and calculated volumes of water (L) applied to the commercial regime (CR) and the irrigation test regime (ITR) in each of the four growing systems between 8 June and 16 September 2012.

| Growing system | Irrigation regime | Irrigation applied | | % of savings | |
|---|---|---|---|---|---|
| | | h | L | Water | Fertigation |
| V-system | CR | 60 | 192 | | |
| | ITR | 14 | 45 | 77 | 85 |
| Traditional | CR | 60 | 192 | | |
| | ITR | 20 | 64 | 67 | 62 |
| Central Leader | CR | 60 | 192 | | |
| | ITR | 22 | 70 | 64 | 70 |
| U-system | CR | 60 | 192 | | |
| | ITR | 20 | 64 | 67 | 70 |

Water productivity values were also calculated for each irrigation regime and for each system (Table 3). The volume of water applied was recorded when ITRs were first applied. The water productivity (WP) values indicated the potential of using irrigation scheduling to reduce the volume of water used to produce 1 kg of Class 1 fruit. A lower WP value indicates a higher irrigation water use efficiency.

**Table 3.** Water productivity values achieved under each irrigation regime for the four growing systems

| Growing system | Irrigation regime | |
|---|---|---|
| | CR | ITR |
| V-system | 24 | 5 |
| Traditional | 35 | 11 |
| Central Leader | 38 | 13 |
| U-system | 27 | 8 |

## Conclusions

- The soil matric potential at which physiological responses to drying soil were first triggered was identified for trees under the ITR in the CL system; leaf elongation rate was significantly slowed at a soil matric potential of -190 kPa.
- A ‘low risk’ irrigation strategy was developed to schedule irrigation in the ITRs in each of the growing systems; irrigation was applied once the lower irrigation set point of -120 kPa was reached.
- Rates of soil drying under the ITRs differed in the four growing systems and this dictated the frequency of irrigation events and the volumes of water applied.
- Tree and fruit physiology were not affected under the ITRs in 2011 and 2012.
- Class 1 yields and components of fruit quality at harvest were not affected by the ITRs in each growing season.
- Water savings of between 48 and 77% were achieved under the ITRs compared to the CRs over the two seasons.
- In 2011 yields of Class 1 fruit were highest under the ITR in the U-system (9.3 kg per tree) and lowest under the CR in the Traditional system (3.7 kg per tree). In 2012 yields of Class 1 fruit were highest under the ITR in the V-system (9.5 kg per tree) and lowest under the CR in the Central Leader system (5.0 kg per tree).
- Average individual fruit mass (and volume) were greatest in the V-system (220 g) and lowest in the Traditional system (180 g).
- The higher yields in 2011 under the ITR, compared to the CR, in the U-system were unlikely to be due to the irrigation treatments.
- The scientifically-derived irrigation scheduling guidelines being developed in this project will help growers to optimise WUE and environmental sustainability of high intensity ‘Conference’ pear production.

## Knowledge Exchange and Technology Transfer activities

- The project aims, objectives and results were presented to BIFGA during a visit to EMR, 25 April 2012.
- Demonstration of TF 198 in CPO to AG Thames, 21 May 2012, EMR.
- Demonstration of TF 198 in CPO to Rupert Kruger (Thames Water) and Sarah Ward (EM Trustee), 13 June 2012, EMR.
- The project aims, objectives and results were presented at the Waitrose Top Fruit Grower Conference 26 June 2012, Waitrose Aylesford.
- Demonstration of TF 198 in CPO to Kent Regional Water Summit, 26 June 2013, EMR.

- Discussion of EMR water research and demonstration of TF 198 in CPO with David Cooper, Jemilah Bailey et al. (Defra), 10 July 2012, EMR.
- Demonstration of TF 198 in CPO to Waitrose Board members and Technical staff, 31 July 2013, EMR.
- Demonstration of TF 198 in CPO to Ziv Charit, Netafim, 4 September 2013, EMR.
- Demonstration of TF 198 in CPO to Alan Turner, KCC, 25 September 2013, EMR.
- Demonstration of TF 198 to Kent Rural Business Group, 26 October 2012, EMR.
- The project aims, objectives and results were presented at the Kent Water Summit: Water security for Farmers and Growers, 12 November 2012, EMR.
- The project aims, objectives and results were presented during a visit to FAST Ltd 30 January 2013, Faversham, Kent.

## Overall Project results

- A new irrigation scheduling strategy has been developed for pear production that reduces losses of water and fertiliser past the rooting zone.
- Water savings up to 77% were delivered without reducing Class 1 yield using the irrigation scheduling strategy. Since nutrients were added at each irrigation event, significant fertiliser savings have also been achieved in the CPO at EMR.
- The lower fertiliser inputs did not cause any visual nutrient deficiencies.
- New fertigation regimes need to be developed to optimise tree nutrition under water-saving irrigation strategies.

## Financial benefits

The true economic value of water used for the irrigation of high-intensity tree fruit orchards is difficult to quantify, as are the financial benefits associated with water savings (unless mains water is used as a source of irrigation water). A full cost/benefit analysis would require three irrigation treatments to be set up at EMR (or elsewhere):

1) A commercial control irrigated using current ‘best practice;
2) The ITR developed in this project;
3) No irrigation applied throughout the season.

Differences in Class 1 yields obtained under the three regimes could then be used to estimate the gain or loss of revenue, which could be balanced against the expenditure needed to implement the different irrigation strategies. This information will be obtained for apple and sweet cherry in a new HDC-funded project (TF 210). The potential to target fertilisers more efficiently to the rooting zone under the ITRs may be of more immediate interest to some growers since there is the potential to reduce both inputs and direct costs.

## Action points for growers

- Consider installing probes to measure soil water availability or soil moisture content within the rooting zone to help develop effective irrigation scheduling strategies.
- Consider installing water meters to accurately record the volumes of water used to produce 1 tonne of Class 1 fruit.
- Consider monitoring water inputs and changes in soil water availability/content in just one block as this will help to improve awareness of the effectiveness of current irrigation strategies and will highlight opportunities for improvement.
- Consider using compost at planting and as a mulch thereafter to help improve soil water retention and limit evaporative losses from the soil surface.

## SCIENCE SECTION

### Introduction

Irrigation is essential for the successful establishment and continued productivity of high-intensity tree fruit growing systems. Modern and traditional orchards also rely increasingly on irrigation to deliver the yields and quality needed for a profitable business (TF 179 Final Report 2011). However, more efficient use of inputs, including labour, water and fertilisers, is vital to the future success of the industry. Seventy six per cent of tree fruit growers farm in areas where water resources have already been classified by the Environment Agency (EA) as being under increasing stress, and abstraction rates in these areas are currently unsustainable (Knox *et al*., 2009). Recent droughts, particularly affecting the southeast and east regions, have highlighted the need for growers to use water more efficiently. Increases in agricultural water demand in the 2050s in England and Wales range from 25% to 180% of current demand (EA, 2008). One useful indicator of aridity that is widely used is the potential soil moisture deficit (PSMD), which represents the balance between rainfall and potential crop water use over the year. It is estimated that in the southeast the average annual maximum PSMDs that currently occur every five years will occur every two years by 2080 and deficits that currently occur every 15 years will occur every five years by 2080. Therefore, there will be an increasing reliance on irrigation to ensure profitable tree fruit production. Future legislation will require that drip/trickle irrigators demonstrate an efficient use of water and current Environment Agency concerns about the impact of horticulture on groundwater quality in the south east will focus attention on improving nutrient use efficiency in tree fruit production.

Current best practice irrigation recommendations for pear are to maintain soil matric potential ($\psi_m$) within the rooting zone between field capacity (approximately -10 kPa) and -30 kPa during flowering and for up to six weeks after petal fall. Soil is then allowed to dry to -60 kPa between irrigation events until early July before irrigation is withheld to encourage the cessation of extension growth and set of the terminal bud. During the latter half of July and during August irrigation should then be scheduled to maintain $\psi_m$ between -10 and -25 kPa. These guidelines for the irrigation of high density orchards were developed overseas and, although they provide a useful starting point, new guidelines that optimise water use efficiency (WUE) and environmental sustainability are needed for UK tree fruit crops grown on different soil types. For example, the recommended $\psi_m$ values for the majority of the season are relatively close to field capacity, which means that irrigation must be applied frequently. Whether irrigation set points could be lowered further without affecting Class 1 fruit yields and quality at harvest was determined in this project.

To encourage research in this area and to provide preliminary data for the development of the project proposal, pump-priming funding was provided by AG Thames Ltd in 2010 to cover the costs of renting/purchasing and installing soil moisture probes in each of the four growing systems in the Concept Pear Orchard (CPO) at EMR. Changes in volumetric soil moisture content (VSMC) at six different depths and $\psi_m$ at two depths were logged continuously over the summer and winter of 2010/2011. Analysis of these data sets indicated that a significant opportunity existed to improve WUE in the CPO at EMR. Research on optimising fertiliser inputs to the different growing systems is beyond the remit of this project but leaching of fertilisers due to over-irrigation would be greatly reduced if run-through was minimised or eliminated. Optimising fertiliser inputs under the new water-saving regimes developed in this project should be carried out in a follow-on project.

The lack of any guidelines about the degree of soil drying needed to set the terminal bud means that, depending on the evaporative demand during that time, very negative $\psi_m$ may develop. In 2010 changes in $\psi_m$ were monitored during the period when irrigation was temporarily withheld to terminate extension growth. Large differences in $\psi_s$ developed during this period and visual assessments confirmed that the trees in the four growing systems were experiencing different degrees of stress. In one case, $\psi_m$ at 40 cm fell below -450 kPa during this period. The effects of this root zone stress on fruit size, quality and storage potential are not known but could be significant. The identification of the minimum (less negative) $\psi_m$ that effectively limits extension growth would enable definitive irrigation guidelines to be developed that reduce the likelihood of yield and quality penalties caused by very low $\psi_m$ that could develop during the time when water is withheld.

Prior to 2011 irrigation to the CPO at EMR had been unscheduled and no account was taken of differences in canopy form or size in the different growing systems. Preliminary data collected in 2010 indicated that soil remained close to field capacity throughout most of the year. Irrigation WUE will be low with this strategy and significant leaching of nutrients past the rooting zone is likely. Our research with other crops (e.g. strawberry, potato) has shown that water savings of up to 40-50% can be achieved compared to current best practice using the novel approaches to irrigation scheduling developed at EMR. In commercial trials Class 1 yields and aspects of fruit quality were also improved and fertiliser savings of up to 21% were achieved. Because $\psi_m$ is not influenced by changes in soil bulk density, the irrigation scheduling guidelines developed in this research will be relevant to the range of different soil types used for pear production in the UK. These guidelines could also provide the basis for future research work on developing deficit irrigation regimes to control vegetative growth, improve fruit quality and storage potential and optimise the use of natural resources.

In this project irrigation test regimes (ITRs) were developed for the four growing systems to try to optimise WUE without reducing Class 1 yields or quality. The approach developed at EMR was to impose temporary and gradual soil drying so that the $\psi_m$ within the rooting zone at which tree physiology is first affected could be identified. The lower irrigation set point for each growing system was then set 40-50 kPa above this value ($\psi_m$ values are negative). This process was repeated at different stages of crop development to determine whether sensitivity to drying soil changes during the growing season. Additional Decagon 10HS probes and multi-depth capacitance probes that measure VSMC were also inserted within and below the rooting zone to help inform the development of the ITRs. The upper irrigation set point was field capacity (*circa* -10 kPa).

A separate but allied commercial project was carried out at G. H. Dean & Co. Ltd in 2011 in a modern Conference pear orchard but the results are not included in this Final Report. In addition, AG Thames provided funds to assess post-harvest quality attributes at three and six months in fruit harvested from each of the growing systems and from fruit taken from trees under the ITR in the V-system. These results are also not included in this Final Report.

## Materials and Methods

### *The Concept Pear orchard at EMR*

All experiments were carried out in the Chingford's / AG Thames' CPO at EMR. The orchard was planted with Conference pears on Quince C rootstocks from 18-20 March 2009 and contains 40 rows of trees spaced 3.5 m apart, with 75 trees in each row spaced 1 m apart. Four different growing systems are being trialled in the orchard (Figures 7 and 8):

1) V-system;
2) Traditional system;
3) Central Leader (or Run-through);
4) U-system.

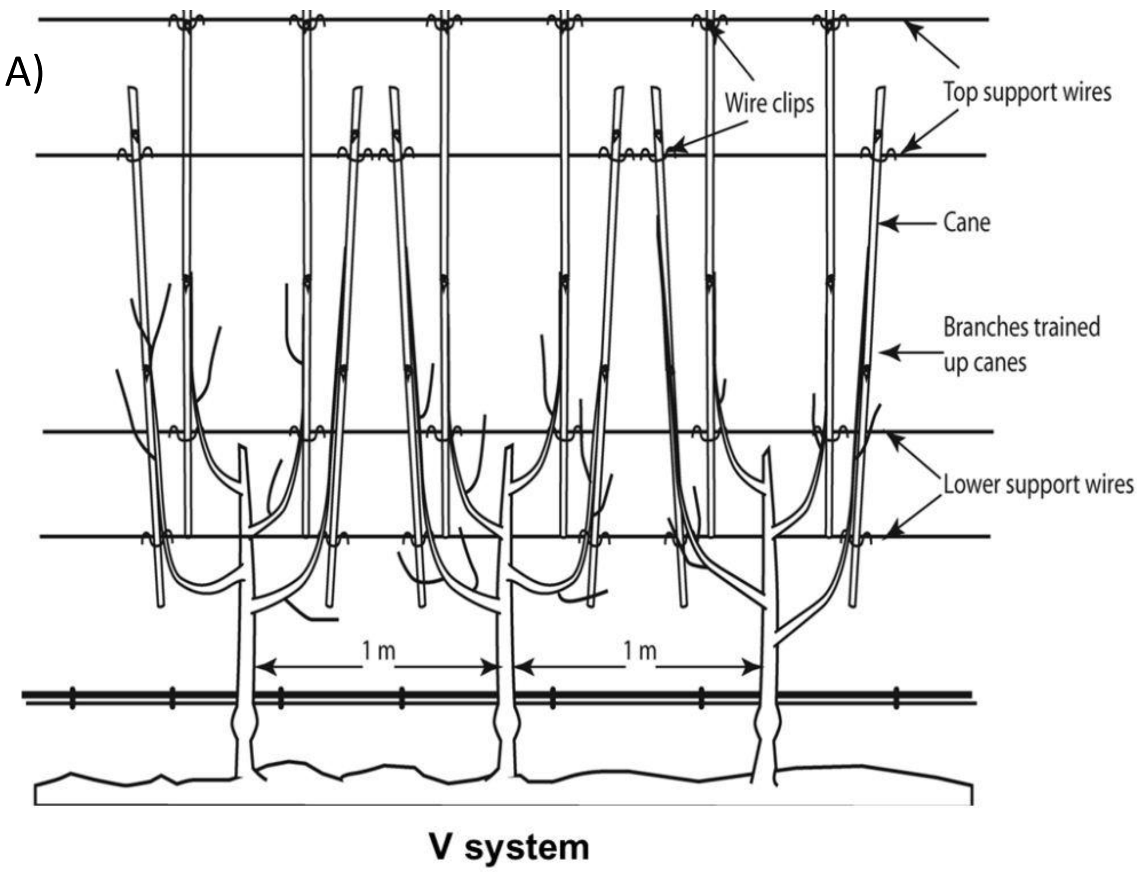
Each system comprises ten adjacent rows within the orchard. All the trees within the orchard receive the same crop husbandry practices (*e.g*. pest and disease spray programmes, fertiliser application, weed control) and up until the beginning of this project, the frequency and duration of irrigation applied to all trees was the same, irrespective of the growing system. Irrigation water was supplied by irrigation lines running along the centre of each row at a height from the ground of 50 cm, with 1.6 L $h^{-1}$ drippers positioned 50 cm apart, directly next to each tree and mid-way between adjacent trees within the row.

### *Experimental design*

Four experiments were set up in the CPO, one for each of the growing systems, with two irrigation treatments per experiment. The two irrigation treatments were:

- A commercial regime (CR) in which the frequency and duration of irrigation events was decided by Graham Caspell, EML's farm manager;
- An Irrigation Test Regime (ITR) in which irrigation was scheduled once a pre-determined $\psi_m$ was reached (see below).

Within each growing system, three central rows each containing 28 trees were selected for inclusion in the experiment. Each row was an experimental block. Half of the trees within each block received the CR and half the ITR. The ITR was imposed by installing a separate irrigation line to 14 trees in the middle of each of the three rows and irrigation to these blocks was controlled using Galcon irrigation controllers in each of the four growing systems. To the north and south of the 14 ITR trees, seven trees receiving the CR were included in the block. Within each experimental block, two CC and two ITR trees were selected on which all physiological and fruit yield/quality measurements were conducted; there were six replicate trees per treatment in each experiment.



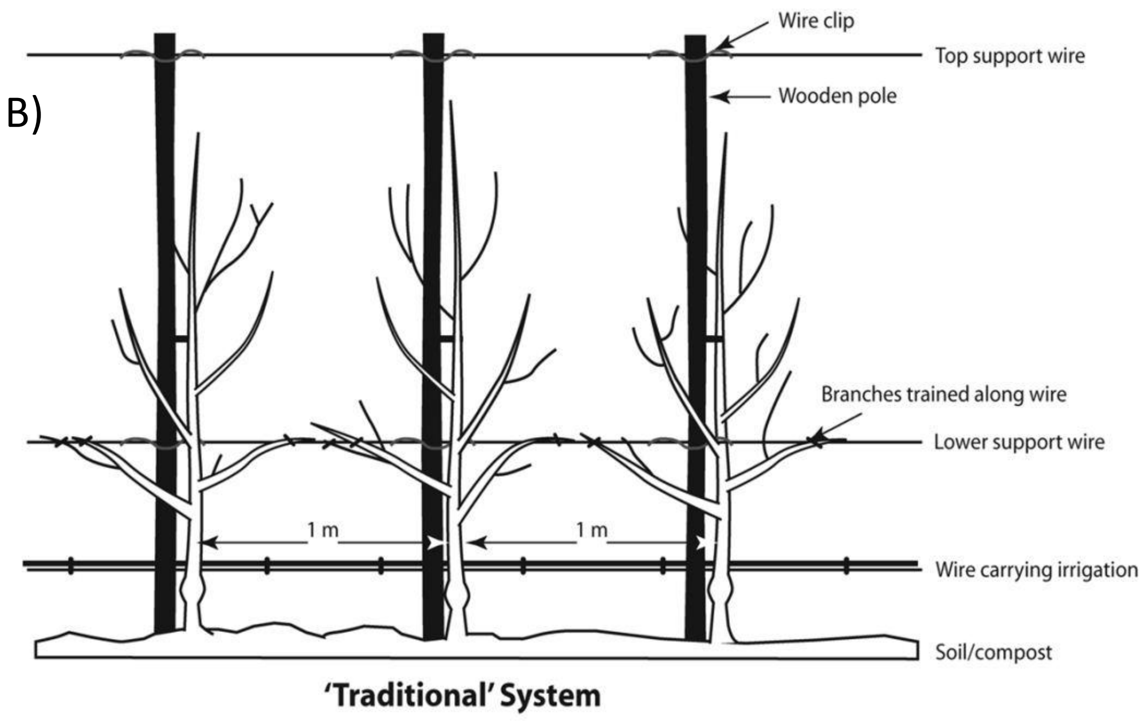




**Figure 7**. A) The V-system and B) the Traditional system being trialled in the Concept Pear Orchard at EMR. Source: Francis Wheatley, AG Thames Ltd.

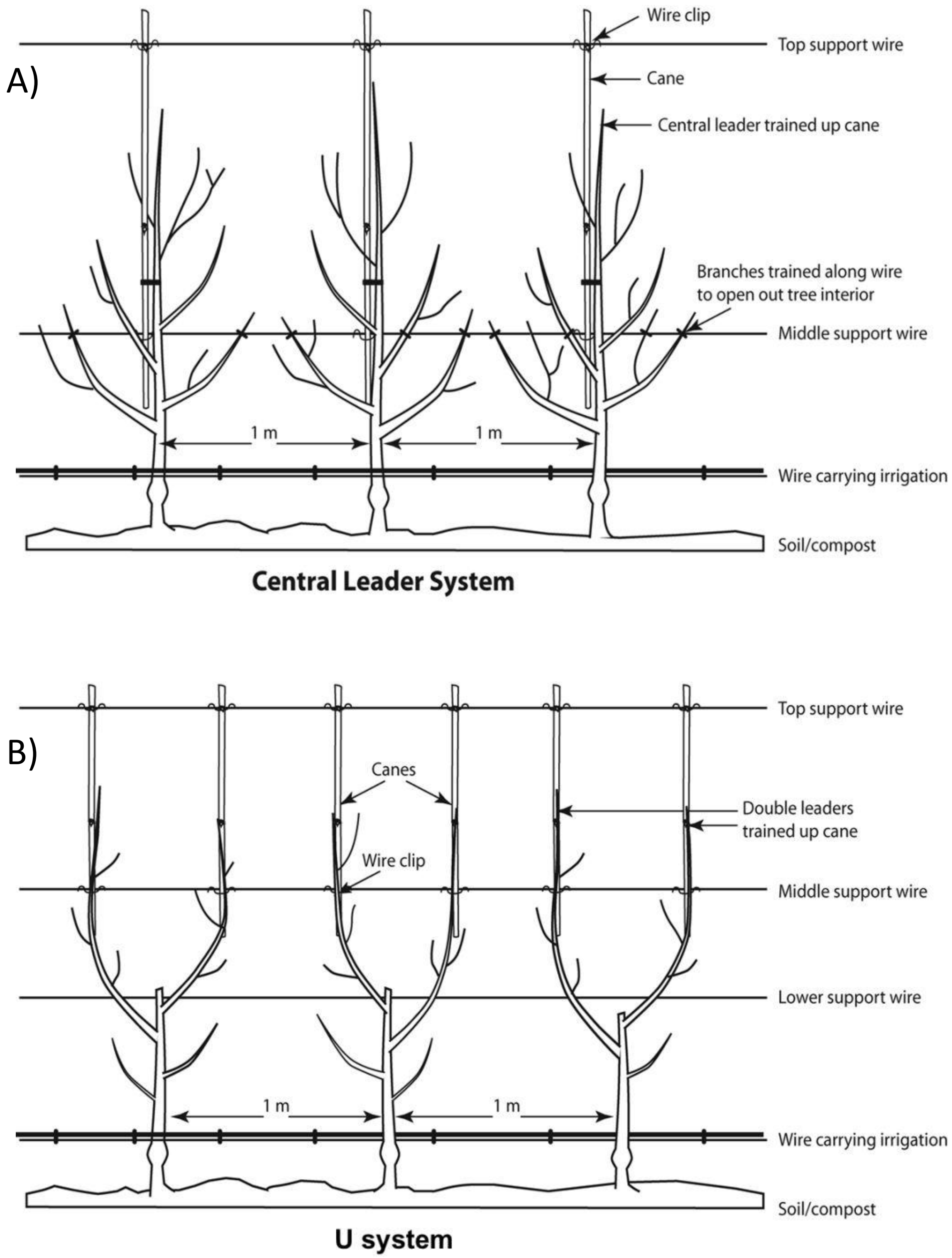



**Figure 8**. A) The Central Leader and B) the U-system being trialled in the Concept Pear Orchard at EMR. Source: Francis Wheatley, AG Thames Ltd.

### *Measurement of volumetric soil moisture content and soil matric potential*

Soil matric potential in each of the four ITRs was monitored hourly from 18 May until 25 November using MPS1 probes (Figure 2 in Grower Summary) connected to EM50 data loggers (Decagon Devices Ltd). In each ITR, an MPS1 probe was inserted within the rooting zone of four representative trees; two at 20 cm and two at 40 cm. Probes were inserted at either 20 or 40 cm depth within 20 cm of the trunk and were positioned directly beneath an irrigation emitter. Data loggers were downloaded daily and the average $\psi_m$ over 40 cm for each ITR was calculated. Volumetric soil moisture content was also monitored continuously, using a Decagon 10HS soil sensor (Figure 9) positioned in each of the four growing systems at a depth of 25-35 cm within 20 cm of the tree trunk. A Sentek EnviroScan multi-depth capacitance probe was installed next to a representative tree in each of the CR and ITR in each growing system by Peter White (Soil Moisture Sense Ltd). Changes in VSMC were monitored at 10, 20, 30 and 50 cm depths and the accumulated soil moisture deficit (SMD) within the top 30 and 50 cm of soil was calculated. To monitor the frequency, duration and volume of irrigation events, ECRN rain gauges connected to EM50 data loggers were positioned directly below individual emitters within the CR and ITR of the V-system.

**Figure 9.** Rain gauge positioned under an emitter to record irrigation volumes in the concept pear orchard at EMR

### *Commercial irrigation regime*

The frequency and duration of irrigation events under the CR (and the majority of the CPO) were decided by Mr Graham Caspell (EML's farm manager) with advice from Mr Henk Nooteboom (Verbeek Boomkwekerijen B.V.). Irrigation was applied for 20 min daily *via* 1.6 L $h^{-1}$ emitters spaced 50 cm apart from white bud (13 April 2012) until 11 August 2012, when irrigation was withheld for several days to terminate extension growth and encourage the terminal bud to set. Irrigation was then applied for 60 min each day from 21 August until 29 August 2012 and thereafter increased to 90 min until harvest on 17 September 2012, to ensure that soil water availability was not limiting. After harvest all trees were un-irrigated throughout autumn and winter 2012-2013.

### *Irrigation test regimes*

Irrigation was applied to all ITR trees in each growing system once the average $\psi_m$ over 40 cm depth had reached the lower set point of -120 kPa. The lower irrigation set point for each ITR was set at 70 kPa above the value that tree physiology was found to be affected in the previous experimental year. Irrigation was withheld from 8 July 2012 until the average $\psi_m$ reached -190 kPa to terminate extension growth and encourage the terminal bud to set. Thereafter, irrigation was applied when the average $\psi_m$ reached -120 kPa. The duration of these irrigation events was adjusted to ensure that the soil in the rooting zone was returned to field capacity but that run-through of water and nutrients past the rooting zone was minimised. Following harvest on 17 September 2012 irrigation to the ITRs was turned off, to replicate the situation in the CR and the commercial orchard.

### *Physiological measurements*

Physiological measurements of leaf stomatal conductance ($g_s$), photosynthesis, leaf ($\psi_L$) and stem ($\psi_S$) water potential were carried out each time that the lower irrigation set point was reached. Midday $\psi_L$ was measured until end of July and thereafter midday $\psi_S$ was used to identify the onset of hydraulic signalling in response to limited soil water availability as this measure is less prone to short-term fluctuations in the aerial environment. Leaf elongation rate (LER) and fruit expansion rate (FER – length and diameter) were carried out weekly from 22 May to 17 September in each of the growing systems. All physiological measurements were carried out on six trees per treatment, selected at the start of the study, in each of the growing systems. Stomatal conductance measurements were carried on one fully-expanded leaf per tree with a steady-state porometer (Leaf-porometer SC-1, Decagon Devices Ltd). Measurements of photosynthesis was carried out on one fully expanded leaf per tree, using a portable infra-red gas analyser (CIRAS-1, PP-systems) with an additional light source powered by a car battery (Figure 10). Midday $\psi_L$ was carried out on one young, fully-expanded leaf on each experimental plant using a Skye SKPM 1400 pressure bomb (Skye Instruments Ltd, UK) (Figure 11); leaves were sealed inside the pressure chamber within 30 s of excision. Midday $\psi_S$ was measured on a young leaf per tree; leaves were covered using an aluminium foil pocket for at least 1 h before measurement. For all experiments, leaf extension was determined by measuring the length of the leaf blade of two young expanding leaves per tree, weekly until maturity; newly expanding leaves were then labelled and measured. In total, three sets of leaf extension measurements were made. The length and diameter of two fruit per tree was measured weekly using digital callipers; fruit diameter was measured at the widest point at two diametrically opposed positions. Non-destructive estimates of fruit volume were made by assuming that fruit were conical in shape and fruit expansion rates were then determined.

**Figure 10.** Measuring photosynthesis on trees under the ITR. Photo taken on 30 August 2011.

**Figure 11.** Measuring leaf water potentials to assess whether trees under the ITR were showing signs of stress. Photo taken on 30 August 2011

### *Fruit yield and quality*

Fruit was harvested from the CPO on 17 September 2012. In each growing system, fruit from the 12 trees on which physiological and fruit growth measurements had been recorded were picked into individual crates, which were then graded into three classes, Class 1 (>50 mm diameter), Class 2 (45-50 mm diameter) and waste (fruit that were <45 mm diameter, misshapen, damaged, where rough russet was present, or deemed to be nutrient deficient, diseased etc.). The number and fresh weight of fruit in each of these classes were recorded, and the reason for classifying individual fruit as waste was noted.

Three Class 1 fruit were selected randomly to enable fruit quality of the individual trees within each CR and ITR and each growing system to be assessed. Skin finish (presence of smooth or rough russet) was assessed and scored on a scale of 1 to 5, 1 being poor, 3 being acceptable and 5 being excellent. Fruit firmness (N) was measured using an LRX penetrometer (Lloyds Instruments Ltd) with an 8 mm penetration probe, providing values of force at maximum fruit load. Juice was also extracted from the fruit and soluble solids content (SSC [%BRIX]) measured with a digital refractometer (Palett 100, Atago & Co. Ltd, Tokyo, Japan).

The remaining 12 experimental trees in each block for the CR and ITR treatments were also harvested and fruit was graded into three classes (as described above) and the fresh weight and number of fruit in each recorded.

### *Statistical analysis*

Statistical analyses were carried out using GenStat 13$^{th}$ Edition (VSN International Ltd.). To determine whether differences between the CR and ITR were statistically significant, within each of the growing systems, analysis of variance (ANOVA) tests were carried out and least significant difference (LSD) values for $p<0.05$ were calculated. Where measurements were carried out on a number of occasions over the growing season, repeated measures ANOVA's were also carried out.

## Results

### *Effects of the irrigation regimes on leaf physiological parameters*

Stomatal conductance averaged across the growing season for each growing system was not significantly different between the irrigation regimes (Figure 12).

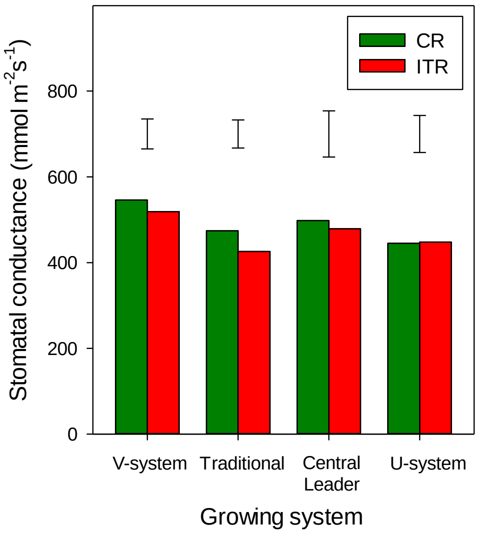



**Figure 12.** Averages values of stomatal conductance for trees under the commercial (CR) and irrigation test (ITR) regimes, for each growing system. Results presented are averaged

across measurement dates during the season. Vertical bars are LSD values at $p<0.05$; there were no statistically significant differences between the treatments.

Stomatal conductances measured on individual dates were also similar under the ITR and CR, indicating that no tree water stress had occurred under the ITR regimes prior to or, on the dates of the measurements. There were no statistically significant differences between the irrigation regimes on leaf water potentials (data not shown). In general, stem water potentials were not affected by the irrigation regimes (data not shown); however, stem water potentials under the ITR regimes were lower than CR in the Traditional and V-systems values just before harvest (Figure 13). Average photosynthesis across the season was not statistically different in any of the growing systems. Photosynthesis rate measured on individual dates was generally similar between irrigation treatments and growing systems but was lower under the ITR regime in the Traditional system on 02 August 2012 and in the V-system on 15 September 2012.

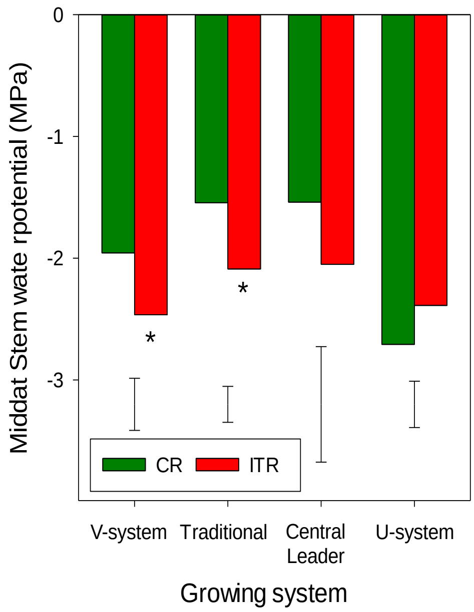



**Figure 13.** Stem water potential for trees under the commercial (CR) and irrigation test (ITR) regimes, for each growing system just before harvest. Results are the average of 6 trees. Vertical bars are LSD values at $p<0.05$; asterisks indicate

### *Fruit growth*

Fruit diameter and length measurements were unaffected by the irrigation regimes (Figure 3 in Grower Summary). Estimates of increases in fruit volume were used to calculate daily fruit expansion rates and these too were unaffected in the V-, Traditional and U-systems (data not shown). For the Central Leader system the fruit expansion rate measured just before harvest was greater under the CR than in the ITR (data not shown).

### *Fruit yields and size at harvest*

The average yield and number of Class 1 fruit per tree was not significantly affected by the two irrigation regimes (Figure 5a in Grower Summary). There were no significant differences in Class 2 yields between the ITR and CR in any growing system (Figure 5b in Grower Summary). In the V-system, there was a higher number of Class 2 fruit under the ITR regime (Figure 14). The mass of waste fruit (due to small size, insect damage, misshape, rots *etc*.) ranged between 1.6 and 3.1 kg per tree. The average weight of individual Class 1 and Class 2 fruit at harvest did not differ significantly between irrigation regimes within a growing system (Figure 6 in Grower Summary); individual fruit weight was lowest in the Traditional system at 172 g and highest in the V-system at 226 g. As anticipated, estimated fruit volumes at harvest mirrored the individual fruit weights noted above, with the lowest volume (98 $cm^3$) in the Traditional system and the highest volume (165 $cm^3$) in the V-system.

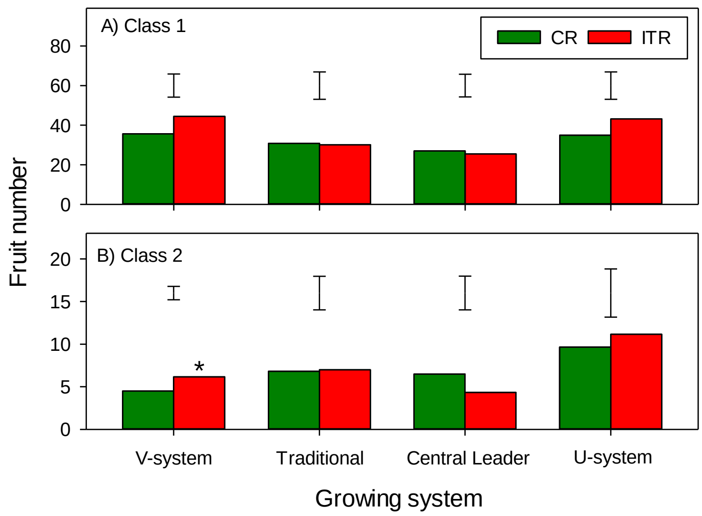



**Figure 14**. Number of Class 1 (a) and Class 2 (b) fruit from trees under the commercial regime (CR) and irrigation test regime (ITR), for each growing system. Results are the average of 6 trees. Vertical bars are LSD values at $p<0.05$; asterisks indicate statistically significant differences between the treatments.

### *Fruit quality components at harvest*

There were no significant differences between irrigation treatments in values of firmness, SSC (% Brix), percentage smooth russet or the colour parameters of fruit harvested from any of the four growing systems (Table 1 – Grower summary). A relatively high degree of russet was noted due to the wet conditions in 2012.

### *Irrigation volumes applied in the two regimes*

Although irrigation was applied daily to all trees from the middle of April 2012, the ITRs were first applied on 8 July 2012 and so the number of hours of irrigation and the resulting volumes of water applied to the ITRs from 8 July to 16 September 2012 in each of the growing systems was calculated (Table 2 in Grower Summary). In the CR irrigation was applied for 20 min daily from 1 July till 11 August 2012, before being turned off to trigger the setting of the terminal buds. Between 21 and 30 August 2012 irrigation was applied for 60 min each day, after which the daily irrigation duration was increased to 90 min until harvest on 16 September 2012. Assuming that two 1.6 L $h^{-1}$ emitters spaced 50 cm apart effectively irrigated each tree, the total volume of water applied to each tree under the CR and ITR in the four different growing systems was calculated (Table 2 in Grower Summary). Water savings of between 64 and 77% were achieved under the ITRs, compared to the CRs. The volume of water applied to the four growing systems under the ITRs also varied; 45 L per tree was applied to the V-system whilst 70 L per tree was applied to the CL system (Table 2 in Grower Summary). Since trees were fertigated at each irrigation event until 30 August 2012, the total amounts of the macro and micro nutrients applied were reduced in proportion to the irrigation volume. Consequently, fertiliser savings of between 62 and 85% were achieved using the ITR. Despite these reduced inputs no visual deficiencies were observed. Water productivity values were also calculated for each irrigation regime and for each system (Table 3 in Grower Summary). The volume of water applied was recorded when ITRs were first applied. The water productivity values indicated the potential of using irrigation scheduling to reduce the volume of water used to produce 1 kg of Class 1 fruit. A lower WP value indicates higher irrigation water use efficiency.

## Discussion

Although irrigation best practice guidelines are available, they were developed overseas and new improved guidelines are needed for use by UK tree fruit growers to ensure that high yields of quality fruit with good shelf-life potential can be produced in an environmentally sustainable way. This is especially important for the UK tree fruit industry since the major areas of production are in regions where pressure on limited water supplies is increasing. Future legislation will also require drip/trickle irrigators to demonstrate good WUE and this will be particularly important in areas classified by the Environment Agency as being under water stress. The scientific underpinning work needed to develop these improved irrigation scheduling best practice guidelines was carried out in this project.

The approach has been developed at EMR and used successfully to deliver significant water savings in soil-grown and substrate-grown strawberry, substrate-grown raspberry, field-grown potato and lettuce and in containerised herbaceous and woody ornamentals. Identifying the $\psi_m$ within the rooting zone at which tree physiological responses to drying soil are first triggered provides valuable information that can inform irrigation scheduling strategies and deliver significant water (and fertiliser) savings. The relationship between $\psi_m$ and tree physiological responses will vary according to evaporative demand, fruit developmental stage and crop load so it is important to establish set points at different times during production in the UK. It is also important that the $\psi_m$ in the active root zone is being measured and the combination of sensors at different depths used in this project gives continuous feedback on rates of water uptake from different soil horizons and how these patterns change as the root system develops. The approach also provides information on the $\psi_m$ needed to impose and manage deficit irrigation strategies such as Regulated Deficit Irrigation (RDI). Although we are only considering irrigation scheduling in this project, the underpinning knowledge needed to implement RDI successfully in high intensity orchards was also developed.

Yields of Class 1 fruit were not affected by the two irrigation regimes in any of the systems. Nevertheless, the fact that the ITRs did not reduce yields in any of the growing systems highlights the potential to deliver significant improvements in WUE and environmental sustainability of tree fruit production without compromising productivity.

Water savings of between 48 and 72% were obtained using the ITRs in the first year of this project. Although this is an encouraging result, expressing water savings in this way can mislead since these figures depend on the efficiency with which water is used in the control treatment. In the CPO at EMR irrigation hitherto has been unscheduled and soil was maintained close to field capacity throughout the top 40 cm of soil for much of 2012. Applying high frequency irrigation (and fertilisers) under these conditions will result in very low WUE values, since most of the applied water and fertilisers will drain past the rooting zone and be lost. The most reliable way to express improvements in WUE is to calculate values of Water Productivity (WP); this is the volume of irrigation water used to produce 1 tonne of Class 1 fruit and this figure allows comparisons to be made between similar growing systems on different farms provided that soil types (and hence soil water hydraulic and retention characteristics) are also similar.

The volumes of irrigation water applied between 8 June and 17 September 2012 to each ITR varied between 45 and 70 L per tree. These differences were due to the frequency of irrigation events needed to maintain $\psi_m$ between the upper and lower set points (-10 to -120 kPa) and the frequency of irrigation, which was determined by the rate at which the trees dried the soil down to the lower irrigation set point. These data suggest that whole-tree water use was highest in the CL system and lower in the V- system.

In this project two different measures of soil water have been used to provide information on root water uptake from different soil horizons; $\psi_m$ which is a measure of soil water availability and VSMC which is a measure of soil water content. From a scientific point of view, $\psi_m$ is the preferred measure since this is the parameter to which trees respond when soil dries down. Soil matric potential is a measure of how much energy the plant has to use to extract water from the soil and a great advantage of this parameter is that it is **not** influenced by changes in soil bulk density, Consequently, the $\psi_m$ at which tree physiological responses first occur in a drying soil should be similar in very different soil types (such as a sandy loam and a clay soil) and so this approach provides an opportunity to develop definitive irrigation set points that are independent of soil type, A further advantage of measuring $\psi_m$ is that an absolute value for field capacity can be obtained (i.e. -10 kPa with the Decagon MPS1 probes). In contrast, the estimated 'full point' used in the EnviroScan system is a relative value measured at a time when soil is assumed to be at field capacity (e.g. after winter rain and before transpirational water loss begins to dry the soil). The 'irrigation trigger' and the 'onset of stress' points are also relative values and for practical purposes, the 'onset of stress' point is assumed to be 50% of the 'full point'. Volumetric soil moisture contents **are** influenced by changes in bulk density and so the 'irrigation trigger' and 'onset of stress' points will vary in different soil types. Nevertheless, the data provided by the EnviroScan probes can be used to schedule irrigation very effectively, provided that data is uploaded regularly and all sensors are working reliably. The best irrigation scheduling tool combines both $\psi_m$ and VSMC; changes in $\psi_m$ are used to schedule the frequency of irrigation and changes in VSMC below the effective rooting depth can be used to inform decisions on the duration of each irrigation event.

## Conclusions

- The soil matric potential at which physiological responses to drying soil were first triggered was identified for trees under the ITR in the CL system; leaf elongation rate was significantly slowed at a soil matric potential of -190 kPa
- A 'low risk' irrigation strategy was developed to schedule irrigation in the ITRs in each of the growing systems; irrigation was applied once the lower irrigation set point of -120 kPa was reached

- Rates of soil drying under the ITRs differed in the four growing systems and this dictated the frequency of irrigation events and the volumes of water applied
- Tree and fruit physiology was not affected under the ITRs in 2011 and 2012
- Class 1 yields and components of fruit quality at harvest were not affected by the ITRs in each growing season
- Water savings of between 48 and 77% were achieved under the ITRs, compared to the CRs, over the two seasons
- In 2011, yields of Class 1 fruit were highest under the ITR in the U-system (9.3 kg per tree) and lowest under the CR in the Traditional system (3.7 kg per tree). In 2012, yields of Class 1 fruit were highest under the ITR in the V-system (9.5 kg per tree) and lowest under the CR in the Central Leader (5.0 kg per tree).
- Average individual fruit mass (and volume) were greatest in the V-system (220 g) and lowest in the Traditional system (180 g)
- The higher yields in 2011 under the ITR, compared to the CR, in the U-system were unlikely to be due to the irrigation treatments
- The scientifically-derived irrigation scheduling guidelines being developed in this project will help growers to optimise WUE and environmental sustainability of high intensity Conference pear production

## Knowledge Exchange and Technology Transfer activities

- The project aims, objectives and results were presented to BIFGA during a visit to EMR, 25 April 2012
- Demonstration of TF 198 in CPO to AG Thames, 21 May 2012, EMR
- Demonstration of TF 198 in CPO to Rupert Kruger (Thames Water) and Sarah Ward (EM Trustee), 13 June 2012, EMR
- The project aims, objectives and results were presented at the Waitrose Top Fruit Grower Conference 26 June 2012, Waitrose Aylesford
- Demonstration of TF 198 in CPO to Kent Regional Water Summit, 26 June 2013, EMR
- Discussion of EMR water research and demonstration of TF 198 in CPO with David Cooper, Jemilah Bailey et al. (Defra), 10 July 2012, EMR
- Demonstration of TF 198 in CPO to Waitrose Board members and Technical staff, 31 July 2013, EMR
- Demonstration of TF 198 in CPO to Ziv Charit, Netafim, 4 September 2013, EMR
- Demonstration of TF 198 in CPO to Alan Turner, KCC, 25 September 2013, EMR
- Demonstration of TF 198 to Kent Rural Business Group, 26 October 2012, EMR

- The project aims, objectives and results were presented at the Kent Water Summit: Water security for Farmers and Growers, 12 November 2012, EMR
- The project aims, objectives and results were presented during a visit to FAST Ltd 30 January 2013, Faversham, Kent

## Overall project results

- A new irrigation scheduling strategy has been developed for pear production that reduces losses of water and fertiliser past the rooting zone
- Water savings up to 77% were delivered without reducing Class 1 yield using the irrigation scheduling strategy. Since nutrients were added at each irrigation event, significant fertiliser savings have also been achieved in the CPO at EMR
- The lower fertiliser inputs did not cause any visual nutrient deficiencies
- New fertigation regimes need to be developed for to optimise tree nutrition under water-saving irrigation strategies

## Acknowledgements

We thank Mr Roger Payne for excellent technical assistance, and Mr Graham Caspell and his team for their helpful advice and support.

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