Project title: Developing precision and deficit irrigation techniques to reduce reliance on PGRs and to optimise plant quality, uniformity, and shelf-life potential in commercial protected pot and bedding plant production

Project number: PO 22

Project leader: Dr Mark Else, NIAB East Malling

Report: Final Report, March 2023

Previous report: Annual Report, January 2021

Key staff: Mike Davies, NIAB East Malling

June Taylor, NIAB East Malling

Hilary Papworth, NIAB

Dr Paul Alexander, Bulrush Horticulture Ltd

Locations of project: NIAB East Malling, New Road, East Malling, Kent ME19 6PR, UK.

NIAB, Lawrence Weaver Road, Cambridge CB3 OLE, UK.

Staplehurst Nurseries Ltd, Clapper Lane, Staplehurst, Kent TN12 0JT, UK.

Neame Lea Ltd, Horseshoe Lane, Spalding, Lincs. PE11 3JB, UK.

Volmary Ltd, Station Rd, Wisbech St. Mary, Cambridgeshire, PE13 4RY, UK.

Industry Representative: NA

Date project commenced: 1 August 2019

DISCLAIMER

While the Agriculture and Horticulture Development Board seeks to ensure that the information contained within this document is accurate at the time of printing, no warranty is given in respect thereof and, to the maximum extent permitted by law the Agriculture and Horticulture Development Board accepts no liability for loss, damage or injury howsoever caused (including that caused by negligence) or suffered directly or indirectly in relation to information and opinions contained in or omitted from this document.

© Agriculture and Horticulture Development Board 2021. No part of this publication may be reproduced in any material form (including by photocopy or storage in any medium by electronic mean) or any copy or adaptation stored, published or distributed (by physical, electronic or other means) without prior permission in writing of the Agriculture and Horticulture Development Board, other than by reproduction in an unmodified form for the sole purpose of use as an information resource when the Agriculture and Horticulture Development Board or AHDB Horticulture is clearly acknowledged as the source, or in accordance with the provisions of the Copyright, Designs and Patents Act 1988. All rights reserved.

All other trademarks, logos and brand names contained in this publication are the trademarks of their respective holders. No rights are granted without the prior written permission of the relevant owners.

The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

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.

Mike Davies

Scientific Support Specialist

NIAB East Malling

Signature Date 30 May 2023

June Taylor

Scientific Support Specialist

NIAB East Malling

Signature Date 30 May 2023

Report authorised by:

Mark Else

Head of Department, Crop Science and Production Systems

NIAB East Malling

Signature Date 30 May 2023

CONTENTS

Grower Summary

Science Section

GROWER SUMMARY

Headlines

- Poinsettia plant height and quality specifications at dispatch were fully met when Regulated Deficit Irrigation (RDI) was used as a non-chemical method of growth control on a commercial nursery;
- Shelf-life potential of RDI-treated plants was improved compared to plants sprayed with PGRs;
- RDI should only be applied to plants with well-developed root systems;
- Objective criteria to assess the quality of poinsettia at dispatch and after shelf-life have been developed;
- The combined use of crop co-efficients and vapour pressure deficits can inform commercial decisions on irrigation scheduling and application of RDI.

Background

In scientifically robust Defra-funded work carried out by NIAB EM and Staplehurst Nurseries Ltd between 2004 and 2008, we showed that Regulated Deficit \irrigation (RDI) applied during the period of rapid stem extension effectively limited plant height so that retailer specifications were met at market date, despite a 90% reduction in PGR use. RDI-treated plants were also more tolerant of chilling stress, and leaf and bract drop during shelf-life tests were reduced by 50% and 90% respectively, compared to well-watered control plants under the commercial PGR programme. Once the RDI technique had been optimised, these benefits were delivered over two consecutive seasons in 2006 and 2007.

Further work funded by the AHDB, led by the University of Lincoln, and carried out at Neame Lea Nurseries in 2017/18 and 2018/19, demonstrated that Deficit Irrigation (DI) could be successfully deployed as a non-chemical means of growth control at scale on a commercial poinsettia crop. However, despite this and earlier successes, several barriers to the widespread commercial uptake of DI and RDI remain, and the industry felt that more convincing evidence of the potential benefits of using these approaches as a non-chemical method of growth control was needed.

In PO 022, our results from statistically robust experiments carried out on a commercial nursery provided unequivocal evidence of the benefits of RDI for height control, quality at dispatch and shelf-life potential of key pot and bedding species. At the outset, we recognised that new approaches were needed to facilitate non-chemical growth control in commercial production systems, and so we assessed and developed tools and technologies that would deliver RDI reliably and consistently in a range of production systems currently used by small-, medium- and large-scale protected pot and bedding growers.

A key aim in PO 022 was to develop objective criteria for the assessment of plant quality at dispatch, following transport and during shelf-life tests to ensure that quality attributes are viewed consistently across the industry. This was achieved for poinsettia and the criteria are available to growers and researchers.

Summary

<u>To quantify the effects of deficit irrigation on poinsettia growth, quality, and shelf-life potential</u>

The potential of using RDI to control stem extension, meet retailers' quality specifications at dispatch, and extend shelf-life potential was investigated on a commercial crop of "Hera" poinsettia at Staplehurst Nurseries, Kent, planted in Week 29. Six irrigation blocks each consisting of four flood-and-drain benches were randomly allocated to either a Commercial Control treatment or an RDI treatment . Decisions on when to apply PGRs and irrigation events to the Commercial Control plants were scheduled by the Staplehurst grower team. Following a single application of PGR at pinching, no further sprays were applied to the RDI crop. RDI was applied during a specific development stage (see below) and during this period, the frequency of irrigation events to the RDI-treated plants was determined by NIAB EM staff. Otherwise, irrigation events to the RDI-treated crop were scheduled by the grower team.

In early September 2019, moisture sensors were placed into nine pots sited across a bench within an irrigation block in both the Commercial Control and RDI treatments. Substrate moisture content averaged every 15 min within treatments was monitored remotely from these sensors with weather station data allowing for calculation of real-time estimates of glasshouse Vapour Pressure Deficits. The NIAB EM team used these real-time data sets to impose the RDI treatment from 16 September 2019 to 10 October 2019. Frequent manual measurements of plant height, substrate moisture content, pore E.C. and plant-and-pot weights were also taken. During this time, four drying cycles were imposed on the RDI crop, with a target lower substrate moisture content of 10-12% before pots were rewetted. Nine fertigation events were applied to the Commercial Control during this period; the duration of irrigation events was the same in both treatments.

Figure GS 1. RDI-treated plants (background) developed paler leaves during the drying down cycles, and bract colouration was delayed compared to Commercial Control plants (foreground). Photo taken on 7 October 2019.

Height data were plotted using a poinsettia growth model used by the nursery. When measured after the end of the RDI treatment on 10 October 2020, the average height of RDI-treated plants was 26.5 ± 0.6 cm, compared to an average Commercial Control plant height of 27.7 ± 0.9 cm.

To establish criteria to objectively assess quality at dispatch, after distribution and during shelf-life

Criteria for the assessment of quality at dispatch were agreed with the Project consortium (see below) and were used by the Staplehurst grower team to ascribe an overall plant quality score. At dispatch, several parameters were measured on randomly selected plants from each treatment, including plant height, canopy width, number of primary and secondary bracts, vertical distance between uppermost and lowermost primary bracts, widths of the largest and smallest bract star, the stage of cyathia development, and the number of leaves on the basal 5 cm of stems.

The only statistically significant treatment difference was the number of primary heads in the Commercial Control plants (5.6) compared to the RDI-treated plants (4.8). Overall, plant quality at dispatch was similar in the two treatments. Average plant heights in the two treatments were similar (CC = 30.2 cm, RDI = 28.9 cm) and these results confirm that effective height control can be achieved using RDI, despite a reduction in PGR use of 85% (1 vs 7 sprays) compared to the Commercial Controls.

After assessment at the nursery, twelve plants from each treatment were selected by the Staplehurst grower team for shelf-life tests.

Figure GS 2. A) RDI-treated and B) Commercial Control plants on the day before dispatch. Photos taken on 7 November 2019.

Criteria for the assessment of plant quality during shelf-life tests were developed by Hilary Papworth (NIAB) and Harry Kitchener (consultant) following discussions with the grower partners. The nomenclature and scoring system to be used to try to ascribe objective quality scores were agreed and used to assess whether RDI impacted on the deterioration of plant quality during an eight-week shelf-life test. The quality criteria are given in the Science Section.

Over the 8-week shelf-life test, leaf abscission was reduced by 50% in plants previously treated with RDI compared to Commercial Controls, and bract abscission was reduced by 90% in RDI-treated plants. Cyathia development was delayed by RDI until week 4 after which values were the same in each treatment. Overall plant quality was higher in RDI-treated plants on five of the seven measurement dates, and plants previously exposed to RDI were aesthetically superior to the Commercial Controls when viewed by the attendees of the AHDB Open Day on 15 January 2020.

To scale-up the DI approach to deliver non-chemical growth control to a commercial poinsettia crop.

Deficit Irrigation was applied to blocks of *ca.* 2,000 “Astro Red”, “Freya Red” and “Infinity Red” plants on flood-and-drain benches at Neame Lea’s Horseshoe Road site. Sensor technologies were installed on 10 September 2020, and real-time data sets were used to schedule the imposition of DI to the three varieties. Irrigation decisions during the period of DI were made in conjunction with the grower team who were monitoring the crops regularly. Plant heights were recorded using tracker software.

The DI treatment was imposed from 5 October until 4 November 2020 during which time up to six drying and re-wetting episodes were applied. A target lower substrate volumetric moisture content of *ca.* 12-13% was used for each variety. At the beginning of November, some plants were still wilting despite the substrate moisture content having been returned to well-watered values. In follow up, it was apparent that the DI treatment had caused significant lower leaf fall in Freya Red, and the quality of the Astro Red and Infinity Red was also lowered. Upon examination, it was noted that the root systems in each of the varieties were not well developed, and were especially poor in Freya Red. Although height specifications were met at dispatch, the grade-out of DI-treated plants was higher than expected. Reasons for the relatively poor root development in some commercial crops at the Neame Lea Horseshoe Road site in 2019 were not known.

To develop tools to deliver Precision and Deficit Irrigation in different growing systems

To date, most sensor-led approaches have been developed for bench ebb-and-flood systems where irrigation is often uniform, and so the variability of pot-to pot-moisture content is low. Capillary matting is viewed as a less expensive alternative method for irrigation control, but variability in pot-to-pot moisture content can be higher. This variability was mapped and quantified in two commercial nurseries growing potted poinsettia on either capillary matting on benches, or on the floor, by multiple sampling of substrate moisture contents before and after irrigation events.

Variability in the bench-top crop was low immediately after an event (1 h) suggesting that the uniformity of irrigation supply and subsequent uptake of water from the capillary matting was good. Subsequent measurements (72 and 120 h after irrigation) showed that the rate of evapotranspiration across the growing area was also even. These results suggest that the use of capillary matting on level benches offers relatively consistent pot-to-pot substrate moisture control, and that this system would be suitable for sensor-based RDI management with relatively few sensors needed. Unfortunately, pandemic-related delays and disruptions meant that our follow-on work to implement RDI in this system could not be started.

Measurements made on the floor-grown poinsettia crop showed a greater degree of variability, and this persisted even after various interventions made by the grower. The largest source of variability was the limited spread of irrigation water along the length of the bays. With this set-up and inherent variability, it would not be economically viable to consider using RDI as a means of non-chemical growth control, as the extent of substrate drying could not be controlled satisfactorily.

To develop approaches and technologies to apply RDI to pack bedding crops

Following extended delays with access to reliable wireless weighing units, two 30Mhz units were received in November 2022, and one was immediately tested at NIAB East Malling on a potted strawberry selection growing in a Controlled Environment room. The second unit was installed at Staplehurst Nurseries in a crop of primrose in December 2022. Both units generated reliable data over several weeks and provided detailed measurements of water lost by evapotranspiration once irrigation to the measurement pots had been withdrawn. The rate of water loss over a 24 h period correlated strongly with ambient vapour pressure deficit (VPD) at each location, and deviations in these rates indicated when plants first perceived a substrate water deficit *i.e.,* the onset of RDI. Crop coefficients were calculated at different developmental stages for each crop, and these will be used post-project - firstly to schedule irrigation to match demand with supply, and secondly to impose RDI to improve resource use efficiency, consistency of plant and fruit quality, assure and extend shelf-life potential, and reduce emission to land, air and water.

Summary of project outputs

1) We have established that wireless substrate moisture sensors and weighing balances

can be operated in real-time in commercial glasshouses reliably, and that the data can be easily viewed remotely on various devices;

2) We have investigated the use of substrate moisture sensors in several growing systems, and have highlighted their respective advantages and limitations;
3) The use of such sensors to measure and map variability in substrate moisture content has been demonstrated in ebb-and-flow and capillary mapping irrigation systems;
4) For longer-term pot crops, the control of growth via RDI can be informed and guided by the real-time substrate moisture data;
5) To decide whether RDI could be applied effectively in any growing system, the degree of variability within each irrigation block should be determined. This is best done by measuring plant-and-pot weights or substrate moisture contents across the growing area before and after an irrigation event. Over-wet or dry areas will reduce the success and benefits of applying RDI;
6) To optimise the quality, and therefore usefulness, of the data sets, more attention should be paid to irrigation system installation and maintenance, for example, bench levelling and irrigation uniformity;
7) More consistency is needed at the pot-filling stage to ensure that the volume/weight of substrate added is similar so that bulk densities are similar in each pot;
8) The use of wireless weighing balances to derive development stage- and variety-specific crop co-efficients is explained;
9) The benefits of using vapour pressure deficit readings and forecasts combined with variety-specific crop co-efficients to improve irrigation scheduling are explained;
10) Advice is available on how to impose RDI on potted and pack bedding using deviations in the rate of change of water loss or substrate moisture content.

Financial Benefits

Cost savings in the purchase and application of PGRs would be realised if RDI was implemented in commercial crops. Reduced fertiliser inputs during the period of RDI imposition would also deliver cost savings. The improved consistency of quality and lower grade-outs resulting from RDI would reduce on-site waste and lower costs and emissions associated with rejections, and the assured shelf-life potential would reduce in-store waste. Taking active steps to transition to net zero emissions goals would also enhance grower businesses' reputations.

Action Points

For growers wishing to reduce plant variability at dispatch by optimising irrigation scheduling:

- Check that your benches are level – using either a laser levelling system or water on the benches;
- Check that bench trays and channels are clean – to ensure an even distribution of irrigation water;
- Check that drainage holes are clean, with mesh grids in place – to avoid blockages and over wetting the substrates;
- Carry out annual irrigation system performance audits - to identify and resolve issues
- Measure the volume of water delivered at each irrigation event - to calculate minimum irrigation durations;
- Deploy pressure regulated irrigation inputs wherever possible - to ensure that target irrigation volumes are accurate and precise;
- Understand the different phytoclimates in your growing areas - use the information to inform decision-making on irrigation scheduling:

For growers considering testing the potential of using RDI as a means of non-chemical growth control in potted poinsettia crops:

- Before imposing RDI, inspect the root system on several plants to confirm that it is fully developed;
- Aim to impose RDI during the exponential phase of stem extension;
- Avoid applying RDI after week 42-43 when bracts are beginning to expand;
- Reduce substrate moisture contents gradually over 2 weeks to allow plants to adapt to the drying rootzone conditions;
- During RDI, withhold irrigation until some plants begin to wilt;
- Use an inexpensive electronic balance to inform irrigation scheduling under RDI;
- Try to avoid imposing RDI during very hot weather;
- Be prepared to see some wilting plants, and a temporary change in leaf colour;
- After the RDI phase, aim to return substrate moisture content to pre-stress values within 1 week.

For growers considering testing the potential of using RDI as a means of non-chemical growth control in spring pack bedding:

- Avoid applying RDI until plants have established and root systems are well developed
- Reduce substrate moisture contents gradually over 2 weeks to allow plants to adapt to the drying rootzone conditions;

- Use an inexpensive electronic balance to inform irrigation scheduling under RDI;
- Be prepared to see a temporary change in leaf colour, or temporary wilting in some varieties;
- Return substrate moisture content to pre-stress values one week before dispatch to make sure that the substrate is thoroughly rewetted for the distribution/retailing phase.

SCIENCE SECTION

Introduction

One of the key priorities of the AHDB Horticultural strategy was to generate innovative R&D and KE to improve the productivity, resilience, and sustainability of horticultural production systems, as well as working with industry to improve access to existing markets. The bedding and pot plant sector is worth approximately £297 million in the UK (Oxford Economics figure, 2018). However, there is fierce competition from the Netherlands, who account for 74% of all UK ornamental imports. They are also world leaders in terms of the agronomy of protected growing.

With impending legislation set to result in the withdrawal of many of the active plant growth regulators (PGRs), and in response to the industry wishing to reduce its reliance on PGRs, the AHDB commissioned work in 2017/18 and in 2018/19 using Deficit Irrigation (DI) to control stem height in poinsettia, which, with the help of substrate moisture sensors, dataloggers, telemetry and grower dashboards, demonstrated that it is possible to control growth without reliance on PGRs. It is important to optimise this approach, and potentially to extend it to other crops, and to include other approaches so that the industry has a suite of options to use. Although the AHDB has continued to fund work on the testing of alternative PGRs, this can only be a short-term solution and it is clear that shoot architecture (shape), bract and leaf quality can be adversely affected by some of these treatments.

The success of the recent AHDB-funded work built on scientifically robust and detailed Defra-funded work carried out by the NIAB EMR Project Leader and Staplehurst Nurseries Ltd between 2004 and 2008. That work showed that a Regulated Deficit Irrigation (RDI) treatment applied during the period of rapid stem extension effectively limited plant height so that retailer specifications were met at market date, despite a 90% reduction in PGR use. RDI-treated plants were also more tolerant of chilling stress, and leaf and bract drop during shelf-life tests were reduced by 50% and 90% respectively, compared to well-watered control plants that received the commercial PGR programme. Once the RDI technique had been optimised, these benefits were delivered over two consecutive seasons.

In this report, RDI is used to define a treatment where the water availability to the roots is purposely limited during a specific developmental stage in order to achieve optimum outcomes, whereas DI is used to describe a more general substrate-drying treatment that is applied to a crop irrespective of the stage of crop development (see Glossary).

In 2016, a “dry growing” regime developed by Neame Lea was used in combination with other strategies to achieve plant height control without reliance on PGRs. The potential to use plant water deficits to control stem height was tested again at Neame Lea in 2017, and this time moisture sensors were used to provide quantitative data on the rate of change of substrate drying and the degree of drying needed to achieve effective height control. Sensors were calibrated for each of the three substrates used in the experiment. Three benches were removed from the commercial irrigation system and the crops were watered by hand; the degree with which the crop was allowed to dry between irrigation events was determined by the grower. Changes in substrate volumetric moisture content (VMC) in these pots were monitored every 15 min throughout the growing season and data was uploaded to the DeltaLINK Cloud to enable “real-time” viewing of the “dry growing” regime developed by Neame Lea.

The degree of the water deficit imposed in “dry growing” regime was informed by identifying the substrate VMC at which visible wilting first occurred under a range of vapour pressure deficits (VPD – the driving force for evapotranspiration). Preliminary work was also carried out to develop variety-specific crop-co-efficients to facilitate scaling-up of the approach across the nursery for poinsettia and other crops where height control is achieved using PGRs.

Similar and successful trials were also carried out at Neame Lea in 2018/19 where DI was used effectively as a non-chemical growth control treatment; 4,000 plants of three poinsettia varieties were grown to market specification without the use of any PGRs, and this was confirmed by leaf residue analysis. Quality of DI-treated plants at dispatch and during and after shelf-life was at least as good as commercial counterparts.

Since our initial work over 14 years ago, there have been many reports in the scientific literature of the effects of DI and RDI on plant growth and quality, and the potential to use this technique as an alternative to PGRs, In the most recent review of this work by M.J. Sánchez-Blanco et al, (2019), the majority of the 113 references refer to published studies on the effects of DI on ornamental plant growth and quality, including work from NIAB EMR and the Project Leader (refs 28-31, 50, 100-101), and see also the published work by Dr Paul Alexander.

The project built on the success of the commercial deployment of DI as a non-chemical means of growth control in commercial poinsettia production funded by the AHDB in 2017/18 and in 2018/19. We continued to develop the technologies and approaches needed to enable the DI work to be scaled-up to deliver non-chemical growth control to 400,000+ poinsettia plants at Neame Lea. We carried out statistically robust experiments at Staplehurst Nurseries to provide unequivocal evidence of the benefits of precision Irrigation (PI) and RDI for height control, quality at dispatch and shelf-life potential of key pot and bedding species. We worked with our industry partners to develop tools, approaches, and technologies to deliver PI, DI and RDI in a range of production systems currently used by small-, medium- and large-scale protected pot and bedding growers. We also developed objective criteria for the assessment of plant quality at dispatch, following transport and during shelf-life tests to ensure that quality attributes are viewed consistently across the industry.

Pandemic-related disruptions and travel restrictions meant that not all of the work on our grower partner nurseries could be completed. In addition, the development of equipment essential to project success was also delayed, and receipt of this equipment in November 2022 meant that only pump-priming research could be carried out. Nevertheless, these datasets will inform post-project exploitation activities in several horticulture sectors, including pack and pot bedding, protected edibles, and soft fruit.

Objective 1: To scale-up the precision and deficit irrigation treatments to deliver non-chemical growth control to 40,000+ poinsettia at Neame Lea

Introduction

In 2019, Neame Lea continued their strategy of growing 400,000+ poinsettia without reliance on PGRs, which they have been doing successfully since 2016. The focus on the work at Neame Lea in 2019 was two-fold: 1) test the potential to use deficit irrigation to limit stem extension in three varieties, and 2) devise approaches that could be used to scale-up the DI approach across the nursery, without reliance on tens of precision irrigation technology units.

Materials and methods

Plants and commercial growing conditions

The deficit irrigation (DI) trial was carried out in the glasshouse facilities at Neame Lea Nursery Ltd, Horseshoe Rd, Spalding PE11 3JB. In Week 29, plants of three varieties, “Astro Red”, “Freya Red” and “Infinity Red”, were potted in industry standard poinsettia mix - 15 mm peat plus 20% by volume medium grade perlite (Figure 1.1). The plants were grown as a commercial crop pinched during the second week of September. Each ebb-and-flow bench initially contained approximately 550-600 pots, reduced to 300-350 at first spacing, with further reductions to 100 plants per bench at final spacing. There were 20 benches of each variety at final spacing in each irrigation block that were individually supplied by a separate solenoid valve.

Figure 1.1. Poinsettia planted in week 29 and covered by fleece to encourage early growth. Photo taken on 1 August 2019.

Spacing was carried out on the three benches by hand (normally automated but necessary due to cable connections between the dataloggers and modems). Overhead watering was done initially by hand. The Neame Lea project team recorded the following aspects of the trial; potting date, spacing dates, plant height and plants per m^2. Environmental metrics were collated via a Hoogendoorn PC, and included glasshouse radiation, temperature, and Relative Humidity. All experimental plants received the same fertigation programme throughout the crop cycle as did the commercial crop.

Deployment of sensors

A technology package consisting of nine SM150T sensors connected to a GP2 Advanced Datalogger and Controller powered by a battery and solar panel, and wired to a modem, was placed on one bench in the middle of the irrigation block in each variety. The sensors were inserted carefully into the substrate of nine representative pots (Figure 1.2) positioned across the length and breadth of each bench on 14 August 2019. Individual pot substrate VMC values were recorded at 15 min intervals and averaged using the GP2 data logger. Telemetry enabled allowing remote access to “real-time” (every 15 min) temperature corrected substrate VMC substrate moisture data and environmental metrics including air temperature and RH from which VPD values was calculated. Data was uploaded to DeltaLINK Cloud and monitored twice daily by the NIAB EMR project team; real-time data was also displayed on a “Grower Dashboard” that was made available to Neame Lea’s Production Manager throughout the trial. The absolute and relative changes in substrate VMC over the previous 24 h were reviewed by the NIAB EMR project team every day before 08:00 and a recommendation on whether to irrigate was sent to the grower via SMS message, and followed with a phone call if further discussion was needed. Weekly plant height measurements were made for each of the three varieties by the Neame Lea team and were uploaded to an on-line tracking software package to which the NIAB EMR team were granted access.

Figure 1.2. An SM150T substrate moisture sensor positioned so that the measuring prongs provide an integrated measure of moisture across the rooting zone. Photo taken on 24 September 2019.

Imposition of Deficit Irrigation

Deficit irrigation was imposed gradually to the three varieties since regular visits by the NIAB EMR project team to measure plant physiological responses to rootzone drying were not possible. An initial DI pre-conditioning treatment was applied from 12 – 21 September 2019 during which time the substrate VMC was reduced to 18% before re-wetting. Deficit Irrigation was then applied from 22 September to 9 November 2019.

The DI strategy for the three varieties had to be revised mid-season to accommodate a change in final height specifications that the Neame Lea management agreed with the customer in Week 38. Prior to that, the Production Manager had been “forcing” the plants to ensure that minimum height specification was reached, and so overnight, plants were above the upper target height by 4 cm or more. Neame Lea have taken the decision not to use any PGR sprays during production, and so consequently, a more aggressive DI strategy was agreed with the Production Manager to try to bring the three varieties plants back within specification. Four cycles of drying and re-wetting were imposed on Infinity Red, five cycles on Astro Red and six cycles on Freya Red, with a target lower substrate VMC of *ca.* 13-14% for each variety. The degree and duration of each drying episode was recommended by the NIAB EMR team following remote analysis of the relationship between VPD and the rate of change (RoC) of substrate drying. Remote recommendations made by the NIAB EMR project team were sense-checked by the Production Manager who, following a visual inspection of the crop, always made the final decision when to end the drying cycle by re-watering.

Results

Substrate volumetric moisture contents in the DI treatments

The duration and severity of the DI treatments applied to the three varieties had to be changed mid-season to try to accommodate the new smaller plant height specification. A more aggressive DI strategy was needed and so the length of time plants remained at the target lower substrate VMC was extended to try to slow stem extension. For example, in Freya Red, the DI drying phase was extended for four additional days between 22 and 26 October 2019 (Figure 1.3). In addition, the number of drying and re-wetting cycles was increased from the usual three or four to five in the case of Astro Red and six for Freya Red (Figure 1.4 A&B).

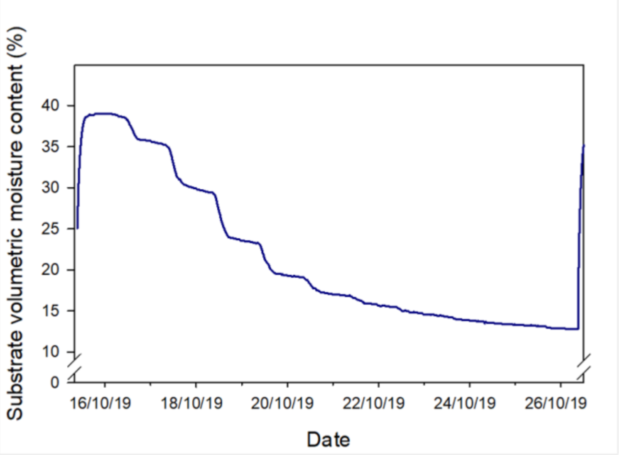


Figure 1.3. Prolonged exposure to dry substrate to try to limit stem extension in Freya Red following the mid-season change in height specification.

Effects of DI on stem extension

Following the enforced change in the DI strategy in week 37, the rate of stem extension in

Astro Red and Infinity Red was slowed within a week and this effect was maintained until the DI treatment was ended on 11 November 2019, so that plant heights were in spec at that time (Figure 1.5 A&C). However, the rate of stem extension in Freya Red was not initially slowed by DI (Figure 1.5B), and so a more severe stress was imposed to try to slow stem extension. Whilst these aggressive DI strategies generally brought plants heights back into, or near to, the new lower height spec., plant quality was impacted (see below).

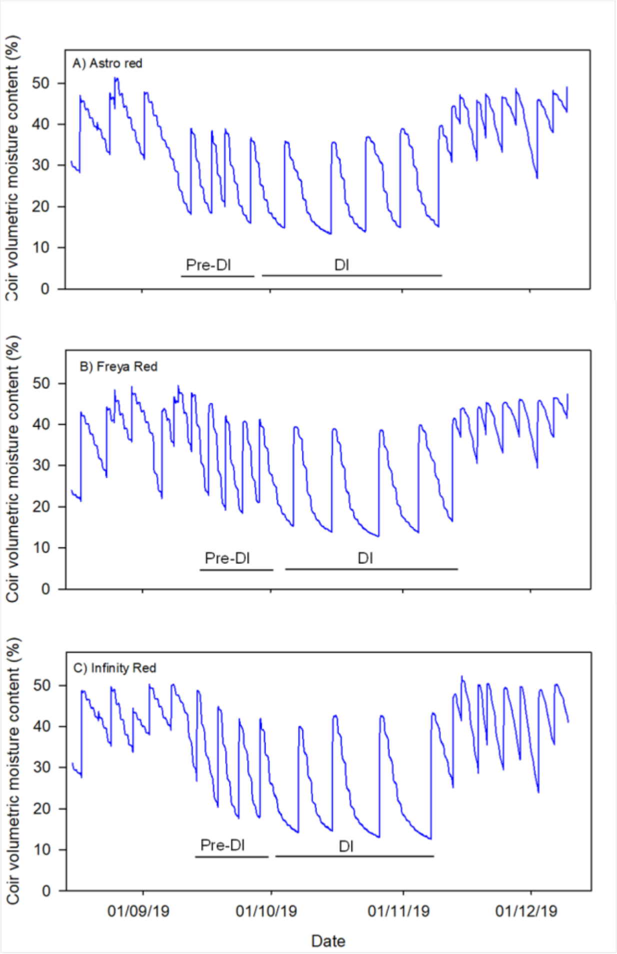


Figure 1.4. Changes in substrate VMC in A) Astro Red, B) Freya Red and C) Infinity Red during the growing season. Values are the mean of readings from nine sensors in each treatment. The duration of the DI pre-conditioning phase in which substrate VMC was reduced gradually, and the DI phases are shown.

Effects of DI on plant quality

In all three varieties, the imposition of DI led to significant leaf abscission from the lower half of the stems (Figure 1.6A). DI and RDI had already been applied successfully to Infinity Red and Astro Red in previous Defra- and AHDB-funded work and the impact on leaf abscission at Neame Lea in 2019 was surprising. Furthermore, some DI-treated Infinity Red plants failed to regain turgor after rewetting (Figure

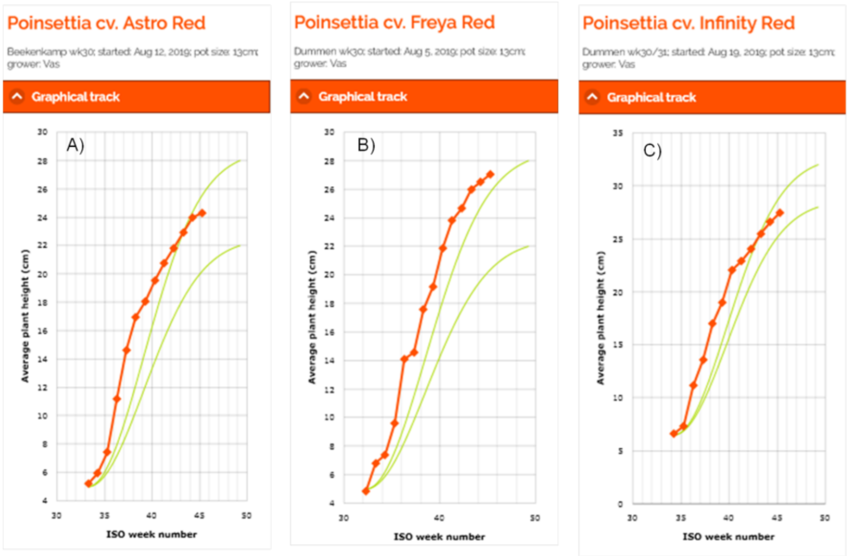


Figure 1.5. Effects of DI on plant height in A) Astro Red, B) Freya Red and C) Infinity Red at Neame Lea Nursery.

1.6B), even though VPD values were low during the recovery phase. On examination, the root systems were poorly developed in many of these three varieties (Figure 1.6C).

Figure 1.6. Plant quality was an issue in the DI-treated plants at Neame Lea in 2019. A) Lower leaf yellowing and abscission in Astro Red on 24 September 2019. B) Wilting and abscising leaves following re-wetting on 8 November 2019. C) Root system development was particularly poor in Freya Red at the end of the RDI treatment on 8 November 2019.

Discussion

The aim of this work was to determine whether RDI could be deployed effectively across a large growing area and so a more straightforward Deficit Irrigation treatment was imposed that relied on the interpretation of remote data sets by the NIAB EM team coupled with observational input from the Neame Lea growing team.

The detrimental effects of the DI treatment on plant quality at Neame Lea have not been seen before in any of our experiments on RDI and other deficit irrigation techniques in a range of crops over the last 15 years. The relatively poor root system in the varieties treated with DI would have contributed to this effect since the roots would have been unable to take up sufficient water to restore shoot turgor after a DI drying episode. The first indication that this was a problem came in early November when the Neame Lea growing team reported that plants of Infinity Red were still wilting after the substrate VMC had been returned to pre-stress values. Subsequent examination of the root systems showed limited development, particularly in Freya Red. The reasons for this are not known and may have included the more aggressive DI strategy adopted to try to bring the plant heights back into specification, but the poor root development was more widespread and was apparent in other varieties outside of the DI trial. There were underlying quality issues reported by the growing team from factors outside of the trial work which led to leaf scorch and abscission in Freya Red (Figure 1.6A), and in other varieties outside of the DI trial. Irrespective of the causes, these results highlight the need for a strong, well established root system to optimise the effectiveness of RDI / DI treatments.

There was also evidence in the Neame Lea results of varietal differences in the response to substrate drying. The responses of Astro Red and Infinity Red were already known but those of Freya Red were not. Stem extension in this latter variety seemed to be less affected by substrate drying and so a more severe stress was needed to elicit a response, but an undesired consequence was the abscission of leaves from the lower and mid stem sections. The different genetic backgrounds of the 20 or so commercial varieties currently grown in the UK will affect their tolerance to rootzone water deficits and it should not be assumed that a single approach will work equally well. Although the response of Hera at Staplehurst to RDI was also unknown, the drying down experiments conducted to establish the substrate VMC needed to trigger wilting was identified and then used to inform the subsequent RDI strategy, which worked well. Given the likely withdrawal of PGRs in the future, and the obvious potential of the RDI technique, it is recommended that preliminary work be carried out on the top six commercial varieties to better understand how to optimise RDI / DI strategies. This could be caried out on a small-scale by the experienced growing teams on commercial nurseries, but the underpinning scientific knowledge gained from replicated and robust experiments is also needed to optimise RDI/ DI strategies.

Despite the disappointing results from the 2019 work at Neame Lea, the team there are committed to continuing with their nursery-wide “dry growing” regime, but they recognise that more experience of the different varietal responses to limiting root water availability and to variable growing conditions more generally is needed, in combination with detailed data sets to inform decision-making during the imposition of DI. This work will be continued post-project.

Objective 2: To carry out statistically robust experiments on a commercial nursery to quantify the effects of deficit irrigation on poinsettia growth, quality, and shelf-life potential

Introduction

An important aim in the first year of PO 22 was to carry out statistically robust experiments so that any treatment differences between Commercial Control plants and RDI-treated plants could be assigned statistical significance, thereby proving that differences were not due to chance. Despite widely publicised reports within the industry from our work spanning two decades demonstrating the benefits of RDI for commercial poinsettia production, uncertainty remains in some growers’ minds about its potential as a non-chemical method of growth control, and about the ancillary benefits. To recap, these benefits have included a reduced reliance on PGRs, the as-yet unquantified cost savings and positive impacts on the environment and workers’ health, and a slowing of deterioration in plant quality during shelf-life. Importantly, and unlike other techniques that can effectively limit stem extension such as blue light treatment or thigmomorphogenesis, no additional capital outlay is needed by the growers to impose RDI, other than that necessary to ensure optimum irrigation system performance.

To prove that these benefits of RDI were not just due to chance, it was necessary to conduct an experiment in which commercial control plants that were sprayed with PGRs could be included, at a site where an experimental design could be easily incorporated into the commercial production of poinsettia, and that was close enough to NIAB EM to enable frequent site visits to make measurements. Previous experience of using RDI and a willingness to accommodate the requests of the NIAB EM science team were also important considerations. For these reasons, experiments were conducted at Staplehurst Nurseries.

Materials and methods

Plants and commercial growing conditions

The RDI experiment was set up in Glasshouse B at Staplehurst Nurseries Ltd, Clapper Lane, Staplehurst, Kent TN12 0JT. The Staplehurst grower team recorded the potting date, spacing dates, plant height and plants per square meter throughout the experiment. "Hera" plants were potted in week 29 in a bespoke poinsettia mix and pinched in Week 33; all plants were sprayed with a Cycocel™ solution shortly after pinching. After this initial PGR spray, 2,000 plants were allocated to the up-coming RDI treatment and were segregated on separate benches. These plants received no further PGR sprays. The plants to be used in the Commercial Control (CC) treatment were treated in the same way as the commercial Hera crop.

Hera plants were moved onto the flood-and-drain benches in Glasshouse B in mid-August 2019. An irrigation block consisted of four flood-and-drain benches each served by a separate solenoid valve, and four blocks were allocated to the CC treatment, and three to the RDI treatment (Figure 2.1). Irrigation / fertigation to the CC crop was scheduled by the Staplehurst

Figure 2.1. The experimental design for the RDI poinsettia experiment at Staplehurst Nurseries Ltd. Blue rectangles represent four benches in a CC irrigation block, red blocks indicate those allocated to the RDI treatment. The position of the nine moisture sensors sited across benches in blocks 4 and 5 is shown.

team who decided on the frequency of irrigation events; the duration of each irrigation event was set at 24 min which ensured an even distribution of water across each flood-and-drain bench in each block. RDI was applied during a specific development stage (see below) and during this period, the frequency of irrigation events to the RDI-treated plants was determined by NIAB EM staff. Otherwise, irrigation events to the RDI-treated crop were scheduled by the grower team. Spacing of all CC and RDI plants was carried out by hand when deemed necessary by the Staplehurst team.

Applications of PGRs

The frequency of PGR applications to the commercial crop was decided by the Staplehurst team after referring to weekly plant height data and variety-specific historical records. For the purposes of this experiment, the first set of height measurements were made by the Staplehurst team on 23 August 2019, several weeks earlier than would be usual. Following the application of Cycocel® at pinching, a further five sprays of Bonzi® were applied to the CC crop between 28 August and 29 September 2019. A second Cycocel® application was made on 4 October 2019, after which time the grower team were satisfied that the CC plants would be within height specifications at dispatch. To reiterate, plants allocated to the RDI treatment received no further PGR sprays after the initial application of Cycocel®.

Sensor installations

The sensor, datalogger and modem technologies were installed by the NIAB EMR project team on 3 September 2019. A technology package consisting of SM150T sensors (Delta-T Devices) connected to a GP2 Advanced Datalogger and Controller powered by a battery and solar panel, and wired to a modem, was placed on a bench in the middle of a CC and a RDI irrigation block (Figure 2.1). The sensors measured the dielectric permittivity of the substrate and were inserted carefully into the rootzone of nine representative pots (Figure 2.2) positioned across the top, middle and bottom of each bench. Individual pot substrate volumetric moisture content (VMC) values were recorded at 15 min intervals and averaged using the GP2 data logger. Telemetry enabled remote access to “real-time” (every 15 min) temperature corrected substrate VMC data and environmental metrics, including air temperature and relative humidity from which Vapour Pressure Deficit (VPD) vales were calculated. Data was uploaded to DeltaLINK Cloud and monitored daily by the NIAB EM project team; real-time data was also displayed on a “dashboard” that was available

Figure 2.2. An SM150T moisture sensor positioned so that the measuring prongs provided an integrated measure of moisture content across the rooting zone. Photo taken on 3 September 2019.

to the NIAB EM team but not to the Staplehurst growing team.

Establishing the relationship between monitored plants and the remaining crop

To determine whether the nine pots into which the SM150T sensors had been installed continued to be representative of the rest of the crop, plant-and-pot weights and corresponding values of substrate VMC were made with a portable electronic balance and a Delta-T "WET" sensor on the "sensor bench" (Figure 2.3) and on one other bench in each irrigation block. Average values were calculated from 18 individual plants on each bench and compared to the overall mean value to inform irrigation decision making.

Figure 2.3. Plant-and-pot weights were measured with a portable electronic balance and a WET sensor was used to measure substrate VMC, pore E.C. and temperature. Photo taken on 3 September 2019.

Establishment of wilting point for Hera

Our previous investigations into the potential of using RDI as a non-chemical method of growth control in poinsettia have not included the variety Hera, and so it was important to establish the relative sensitivity of this variety to rootzone water deficits, and its subsequent recovery upon re-wetting. Six plants were randomly selected from benches within each irrigation block and placed on upturned pots, thereby removing them from the flood-and- drain irrigation system on 11 September 2019. Subsequent measurements of plant-and-pot weights and substrate VMC values were made frequently by NIAB EM staff over the next 5 days at the same time each day, and the rate of evapotranspiration over the previous 24 h was calculated. The plant-and-pot weight and substrate VMC at which visible wilting first occurred was noted, as was the value at which plants failed to regain turgor following a night period (Figure 2.4). Plants were then re-watered and returned to the bench on 15 September 2020. The extent of turgor recovery (absence of wilting) in the morning was noted by the grower team. This exercise was repeated several times over the growing season to identify the degree of substrate drying needed to induce mild wilting which, in our experience, is necessary before effective height control can be achieved during the exponential phase of stem extension.

Figure 2.4. Pots were removed from the irrigation bench and the plants allowed to dry until they failed to recover turgor following a night period. Photo taken on 15 September 2019.

Imposition of RDI

Each day throughout the RDI period, the absolute and relative changes in temperature corrected substrate VMC values over the previous 24 h were reviewed in the Cloud Report by the NIAB EM project team before 08:00 and a recommendation on whether to irrigate was sent to the grower team via a WhatsApp group that also included the NIAB EM project team. Follow-up ‘phone calls were made if further discussion was needed, or if the grower team were concerned. RDI was applied during a specific development stage (see below) and throughout this period, the frequency of irrigation events to the RDI-treated plants was determined by NIAB EMR staff. Otherwise, irrigation events to the RDI crop were scheduled by the grower team, although recommendations were sometimes made by the NIAB EM team.

The NIAB EM team used the real-time data sets from the SM150T sensors to impose the RDI treatment from 16 September 2019 to 10 October 2019, although frequent visits to site were made to make measurements of plant height, substrate moisture content, pore E.C. and plant-and-pot weights. A weather station also provided real-time readings of photosynthetically active radiation (PAR), and air temperature and RH measurements enabled estimates of VPD in the glasshouse to be calculated (Figure 2.5).

Figure 2.5. A) The air temperature and RH sensor and B) the PAR sensor above the crop used to monitor conditions in the glasshouse at Staplehurst. Photos taken on 12 September 2019.

During the period of RDI, nine fertigation events were applied to the CC crop; the duration of irrigation events was the same in both treatments.

During the drying episodes, the NIAB EMR team monitored remotely the changing relationship between VPD and the rate of change (RoC) of substrate drying. Deviations in this relationship indicated that plants were beginning to perceive a rootzone water deficit stress that triggered gradual stomatal closure, and our on-site measurements confirmed when the stress was sufficient to slow stem extension and cause mild wilting. This approach enabled the NIAB EMR team to schedule the degree of substate drying needed to limit stem extensions and to identify remotely when an irrigation event should be scheduled to end a particular RDI drying episode.

Four drying and re-wetting cycles were imposed on the RDI crop, with a target lower substrate moisture content of 10-12% before pots were rewetted. The length of time that plants were held at this lower value was determined by the NIAB EMR team, using information from the changing relationship between VPD and the RoC of substrate drying, and estimates of likely VPD values over the next 24 h.

Measurements of plant height were made once or twice weekly on six labelled plants within the CC and RDI irrigation blocks by the grower team. More detailed measurements of plant height were made weekly by the NIAB EMR team. Height data were plotted using a poinsettia growth model used by Staplehurst Nursery.

Returning the RDI plants to commercial control

The effects of the RDI treatments on stem extension rates were monitored closely to identify the time to return the substrate VMC to pre-stress values. Once the NIAB EMR team were confident that a post RDI stress increase in stem height of around 4 cm over the 4 weeks to dispatch could be accommodated whilst keeping below the maximum height specification, the RDI plants were returned to pot capacity over 2 days and irrigation control was handed back to the grower team.

Measuring plant quality attributes at dispatch

Criteria for the assessment of quality at dispatch agreed with the Project consortium (see Objective 5) and were used by the Staplehurst grower team to ascribe an overall plant quality score. At dispatch, several parameters were measured on randomly selected plants from each treatment, including plant height, canopy width, number of primary and secondary bracts, vertical distance between uppermost and lowermost primary bracts, widths of the largest and smallest bract star, the stage of cyathia development, and the number of leaves on the basal 5 cm of stems.

Shelf-life tests

After assessment at the nursery, twelve plants from each of the CC and RDI-treated plants treatment were selected by the Staplehurst team for shelf-life tests. These plants were labelled, sleeved, placed in trays in boxes and transported by car on the same day to the shelf-life facility at Neame Lea Nursery. Dataloggers were placed inside the boxes to record conditions during transport and relocation.

Statistical analyses

Statistical analyses were carried out using Genstat 14th Edition (VSN International Ltd). To determine whether differences between irrigation treatments were statistically significant, analysis of variance (AVOVA) tests were carried out and least significant difference (lsd) values for $p<0.05$ were calculated.

Results

Substrate moisture contents in the two treatments

The ranges of substrate VMC values recorded over the season in the CC and RDI treatments are shown in Figure 2.6 (A&B). In the CC plants, values of substrate VMC ranged from a low of 17% on 16 September 2019, to a high of 42% on 3 November 2019 just before dispatch, but generally values were maintained between 20 and 40% (Figure 2.6A). The aim in the RDI treatment was to avoid large fluctuations in substrate VMC as previous work has shown that these can reduce plant quality, uniformity, and robustness. Seventeen 24-min irrigation events were applied from 11 September to 31 October 2018 (Figure 2.6B).

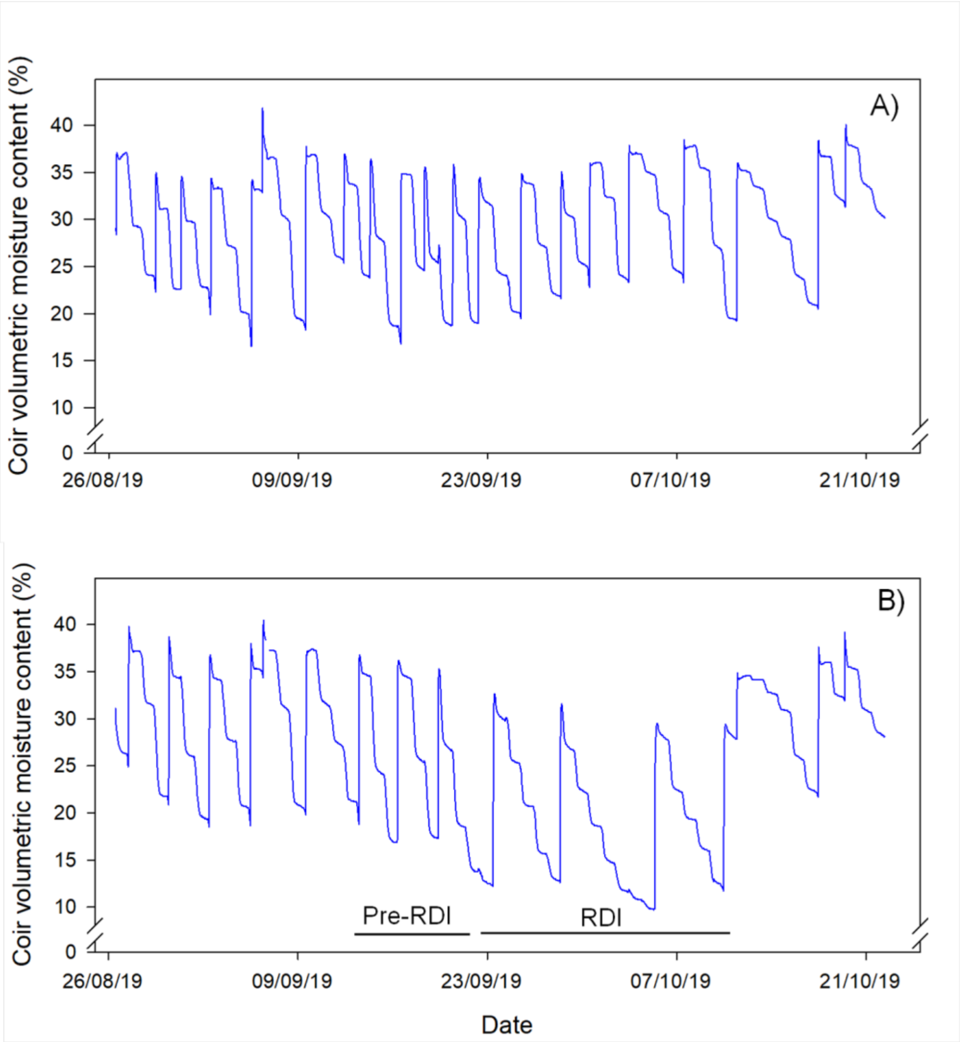


Figure 2.6. Changes in substrate VMC in A) Commercial Control and B) RDI pots during the growing season. Values are the mean of readings from nine sensors in each treatment. In B), the duration of the RDI pre-conditioning phase in which substrate VMC was reduced gradually, and the RDI phases are shown.

Hera responses to substrate drying and rewetting

When irrigation was withheld from six Hera plants over five consecutive days during early September 2019, plant and pot weights decreased by a total of *ca*. 200 g with a corresponding change in substrate VMC of 20% (Figure 2.7A&B). Pore E.C. values were variable over this time (Figure 2.7C) and were likely influenced by the increasingly dry substrate, and so values should be viewed with caution and not over-interpreted. Initially, rates of evapotranspiration were high with the plants transpiring about 65 g of water per day, but as substrate VMC values fell below 25%, gravimetric estimates of evapotranspiration rates were reduced, indicating that stomata were closing in response to rootzone water stress (Figure 2.7D). At this point, on 15 September 2019, visible wilting was apparent at 10:30 (Figure 2.8A). The six plants were then rewatered to return substrate VMC values to pre-stress levels. Within 24 h of rewatering previously wilted plants, all plants regained turgor and were indistinguishable from their well-watered counterparts (Figure 2.8B). These data were used to inform the choice of the target substrate VMC values to be used in the first phase of the RDI treatment.

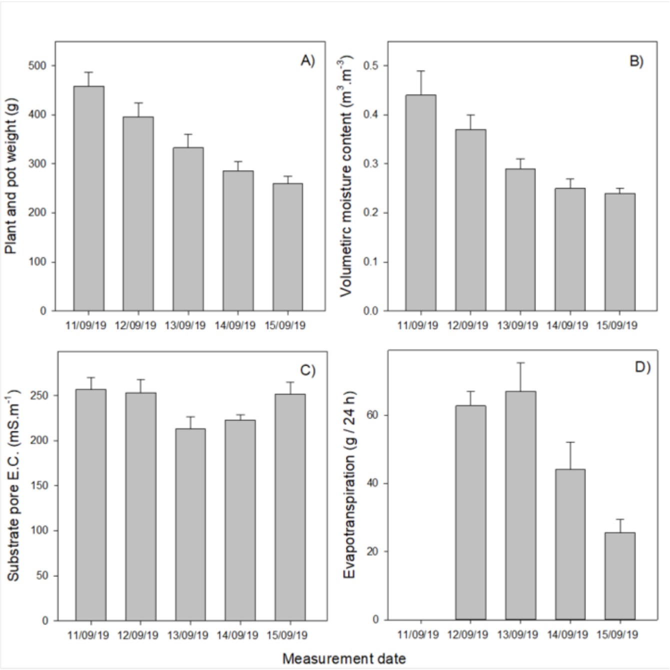


Figure 2.7. Changes in A) plant-and-pot weights, B) substrate VMC values, C) substrate E.C. and D) evapotranspiration rate during a period in which irrigation was withheld. Values are means of six

Figure 2.8. A) Hera plants wilting after 5 days without irrigating. After irrigation, plants had regained turgor the following day. Photos taken on 15 & 16 September 2019.

Diurnal changes in air temperature, PAR and calculated VPD were recorded throughout the 5-day drying cycle (Figure 2.9). The changes in substrate VMC, plant-and-pot weights and daily total VPD were used to calculate crop co-efficients that will be used in our future work to schedule irrigation and RDI using predicted glasshouse VPD values.

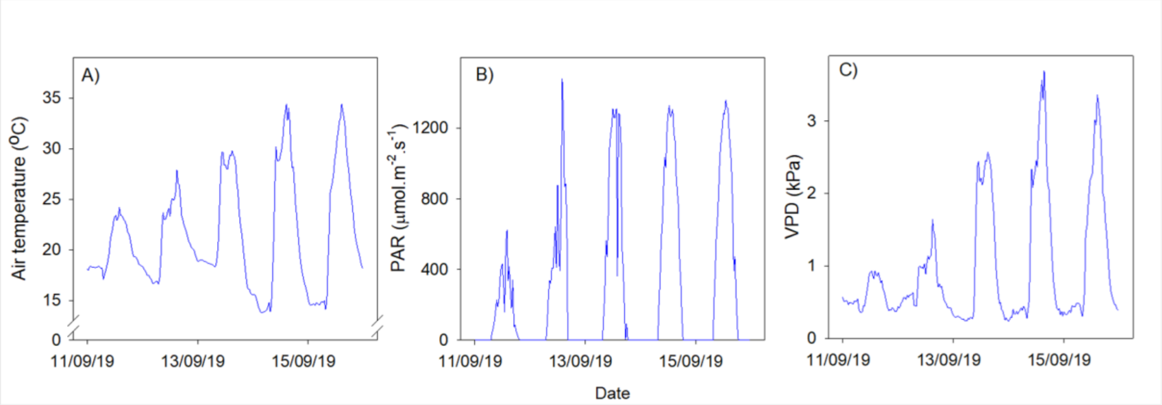


Figure 2.9. Diurnal changes in A) air temperatures, B) PAR and C) VPD during the 5-day drying cycle imposed to establish the wilting point in Hera.

Quantifying the degree of variability substrate VMC across and between benches

A series of measurements were made at 18 specific locations on selected benches in the CC and RDI irrigation blocks to assess the variability in plant-and-pot weights and substrate VMC across the bench and between benches within irrigation blocks. Substrate VMC, pore E.C. and substrate temperature were measured with a WET sensor and plant-and-pot weights with a battery-operated electronic balance (Figure 2.3). These measurements were made on 14 September in the RDI pre-conditioning phase, on 26 September in the middle of the RDI treatment, and on 2 October 2019 towards the end of the RDI treatment. Measurements were plotted as contour maps to give a visual representation of the variability in the measured parameters across and between the benches (Figure 2.10). During the pre-conditioning phase, the plant-and-pot weights on bench #2 in RDI irrigation block 5 varied from 440 – 500 g (Figure 2.10A), while those on bench #2 in CC irrigation block 4 ranged from 480 – 550 g (Figure 2.10B). The wetter area in the middle of the bench (Figure 2.10A) was under the roof vents. Overall, the low degree of variability across benches and the marked differences between the RDI and CC treatments gave confidence that that the irrigation system

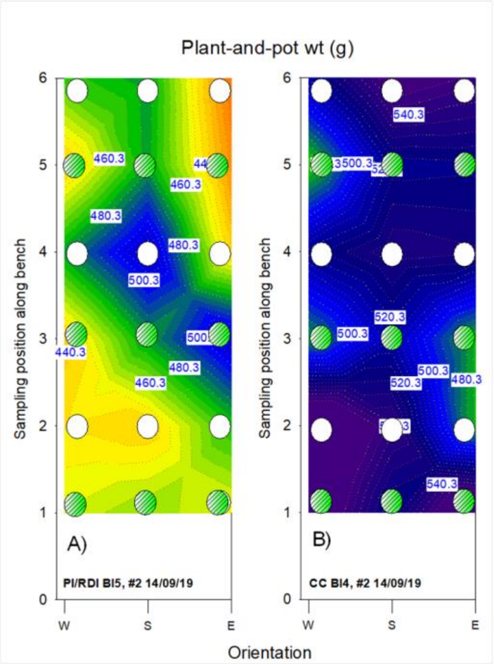


Figure 2.10. Contour maps of plant-and-pot weights across the bench in A) RDI and B) the CC treatments. Circles represent measurement points and green circles show the position of pots in which SM150T sensors were installed. Blue colours indicate wetter substrate and green-yellow colours drying substrate.

performance in the trial area was good enough to support the application of the RDI treatment. Similar results from 2 October 2019 when RDI plants were approaching the target lower substrate VMC confirmed that variability across and between benches was low at this critical time (Figure 2.11).

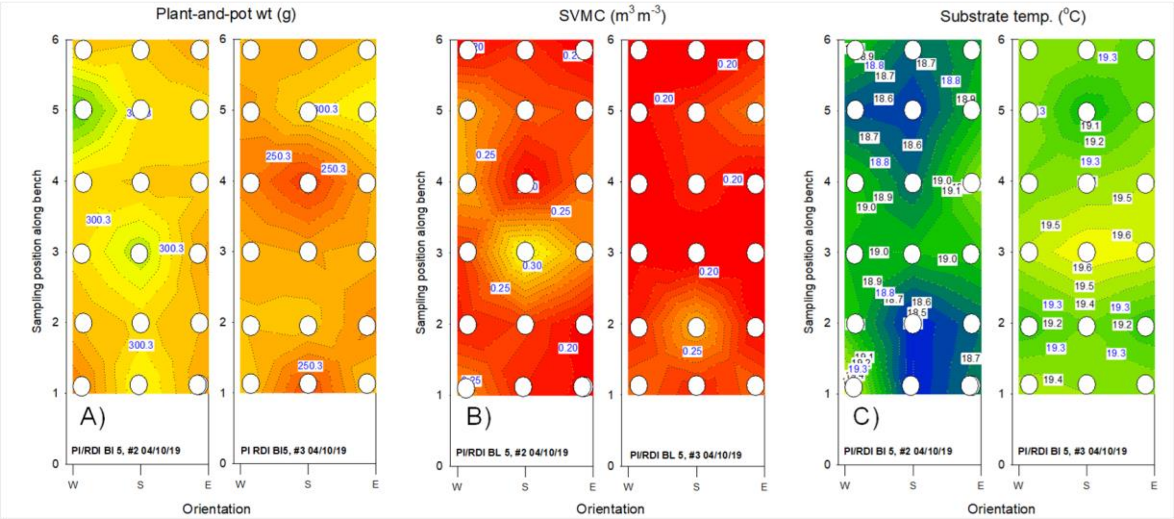


Figure 2.11. Contour maps of A) plant-and-pot weights, B) substrate VMC and C) substrate temperature across two benches in RDI irrigation block #5. Circles represent measurement points. In A) orange indicates lighter pots, in B) red indicates drier substrate, and in C, yellow indicates warmer substrates.

Changes in the rate of change of substrate drying under RDI

The “stepping” observed in the graphs of substrate VMC during the RDI drying phases reflect differences in rate of plant water use between day and night (Figure 14). Changes in the slope of the decrease in substrate VMC during the daytime were used to infer when the RDI-treated plants were beginning to perceive a rootzone water stress (Figure 2.12). On consecutive days with a similar VPD, a change in this slope was interpreted as a slowing of water loss from the shoots due to progressive stomatal closure triggered by the limiting water availability in the rootzone. These responses were used by the

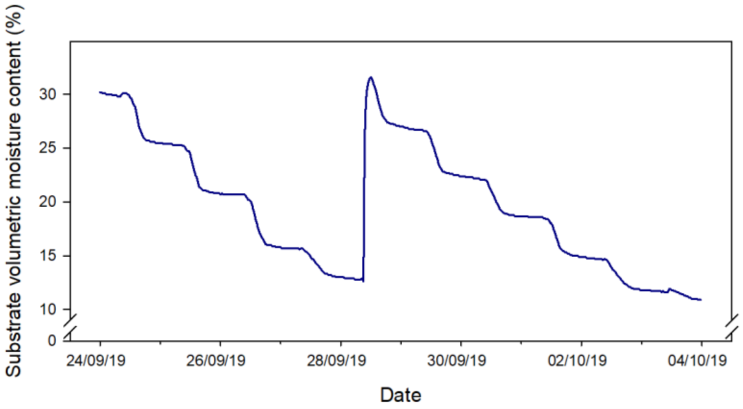


Figure 2.12. Differences in plant water uptake during the day and night cause characteristic “stepping” In the substrate VMC traces. The slope of these steps can be used to identify when a rootzone moisture deficit stress triggers partial stomatal closure, indicating that the plants are perceiving the stress.

NIAB EM team to decide when to end a particular drying cycle by requesting an irrigation event.

PGR control of plant height in Commercial Control plants

The PGR applications were applied to the CC Hera crop in two phases; the first in weeks 33-35, and a second more intensive phase in response to rapid stem elongation noted between weeks 37 and 38 (Figure 2.13 A&B). The PGR programme effectively slowed stem elongation so that plant height tracked along the upper target value until the spray programme was ended in week 40 to avoid damaging the expanding bracts. Late season stretch was around 3 cm and so CC plants were within height specification at dispatch.

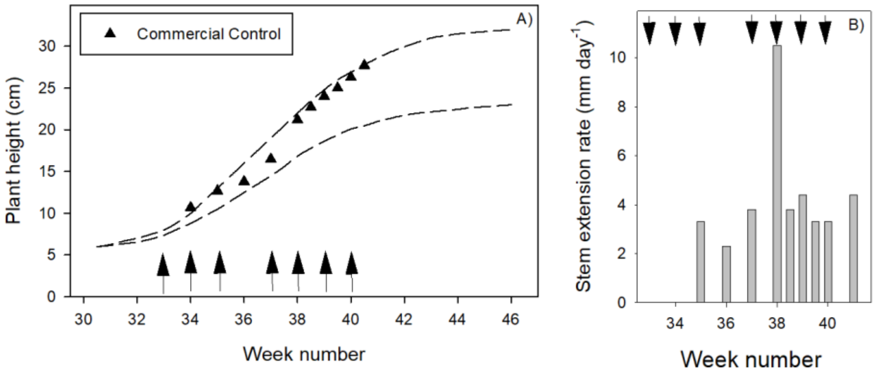


Figure 2.13. A) Plant height increases over the season and B) the rate of stem extension in Commercial Control plants. Values are means of six replicate plants. Arrows indicate the timing of PGR applications. In A) plants heights are plotted relative to the upper and lower height specifications for the crop.

Effects of RDI on Hera stem extension

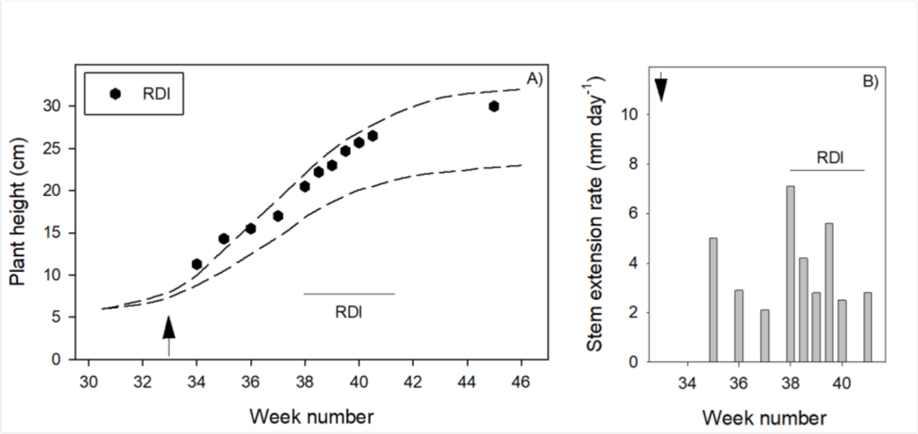


Figure 2.14. A) Plant height increases over the season and B) the rate of stem extension in RDI-treated plants. Values are means of six replicate plants. Arrows indicate the timing of PGR applications. In A) plants heights are plotted relative to the upper and lower height specifications for the crop.

The number of RDI drying episodes and the duration of maximum rootzone stress at each cycle was decided by the NIAB EMR team after referring to the most recent plant height data provided by the Staplehurst team (Figure 2.14A) and to interim measurements made by the visiting NIAB EMR team. The imposition of RDI coincided with rapid stem extension between weeks 37 and 38, and the effect of the first cycle of drying on stem extension rate was measurable within 1 week (Figure 2.14B). A similarly rapid response was seen in week 40. The RDI treatment was ended in week 41 since the NIAB EMR deemed that height control had been achieved and any late season stretch could be accommodated. Continuing RDI into week 42 may have adversely affected bract expansion.

Visual differences in the CC and the RDI crops

Visible differences in leaf colour were noted towards the end of the RDI treatment; leaves on RDI-treated plants were a paler green (Figure 2.15), although this difference was not detected with a SPAD meter (data not shown). This was presumably a response to the more limited supply of nutrient elements to the RDI-treated plants since only four fertigation events were applied during the RDI period, compared to nine fertigation events received by the CC plants. Leaf samples were sent to NRM for analysis, but results showed no treatment differences in the foliar concentrations of micro- and macro-nutrients (data not shown). Following the return to the commercial fertigation regime, leaf colour in RDI plants was restored by dispatch (8 November 2019).

Figure 2.15. RDI-treated plants (background) developed paler leaves during the drying down cycles, and bract colouration was delayed compared to Commercial Control plants (foreground). Photo taken on 7 October 2019.

The other notable treatment difference was a delay in the onset of bract colouration in the RDI-treated plants compared to CC plants (Figure 2.15). This was presumably a consequence of the limited use of PGRs which are known to accelerate bract formation and cyathia development.

Plant quality at dispatch

The quality attributes assessed at dispatch were agreed by the consortium(see Objective 5) and are listed in Table 2.1. Twelve plants were selected at random from the CC and RDI blocks by the Staplehurst team who allocated an overall quality score to each plant. The NIAB EM team measured the other attributes.

The only statistically significant difference noted at dispatch between treatments was the average number of primary heads which was greater in the CC plants (5.6 vs 4.8). The bract stars were generally wider on RDI-treated plants, but this difference was outside of statistical significance. There were no issues with the loss of leaves on the basal portions of the stems and overall quality score allocated by the grower team was similar for RDI-treated and CC

Table 2.1. Poinsettia quality parameters measured at dispatch on 12 Commercial Control and 12 RDI-treated plants; mean values are presented. An f probability value (*p* value) of less than 0.05 indicates a statistically significant difference between mean values, indicated by an asterisk. Corresponding least significant difference (5%) values are also presented.

	Treatment Means			
Quality parameter	CC	RDI	Prob(f)	lsd (5%)
Plant-and-pot weight (g)	573	551	0.213	35.9
Plant height (cm)	30.2	28.9	0.575	4.73
Cyathia stage (1-5)	2	2	-	-
Number of Primary heads	5.6*	4.8	0.015	0.59
Number of secondary heads	2.2	2.3	0.847	0.88
Vertical distance between uppermost and lowermost primary bract (cm)	5.5	4.3	0.135	1.56
Diameter of widest bract (cm)	8.8	8.7	0.501	0.51
Width of largest bract star (cm)	24.6	26.2	0.098	1.90
Width of smallest bract star (cm)	18.8	20.3	0.135	2.00
Number of leaves on basal 5 cm of stem	3.2	3.3	0.92	1.71
Quality Score (1 = poor, 5 = excellent)	4.3	4.2	0.813	0.72

Figure 2.16. A) RDI-treated and B) Commercial Control plants on the day before dispatch. Photos taken on 7 November 2019.

plants in this random sample. There were no visible differences between CC and RDI-treated plants (Figure 2.16).

Shelf-life test

The quality criteria developed by the consortium to assess quality more objectively during shelf-life are given in Appendix 1. The rate of deterioration in plant quality of CC and RDI-treated plants over the 8-week shelf-life test was significantly affected by irrigation treatment. Leaf abscission was reduced by 50% in plants previously treated with RDI compared to CC plants, and bract abscission was reduced by 90% in RDI-treated plants; both differences were statistically significant ($p<0.05$) by Week 4 (Figure 2.17 A&B). Cyathia development was delayed by RDI until week 4 after which values were the same in each treatment (Figure 2.17C). Overall, plant quality was higher in RDI-treated plants on five of the seven measurement dates (Figure 2.17D), although there was some variability between scores on different measurement dates that stemmed from different personnel making the assessments. There remained then a degree of subjectivity in allocating overall quality scores criteria that were followed on each occasion, and so further refinement of the scoring system is needed. This was also apparent when the plants were viewed at the end of the 8-week shelf-life trial; although similar quality scores were allocated in the in the final week of the trial, the RDI-treated plants were visibly better than the Commercial Controls (Figure 2.18 A&B).

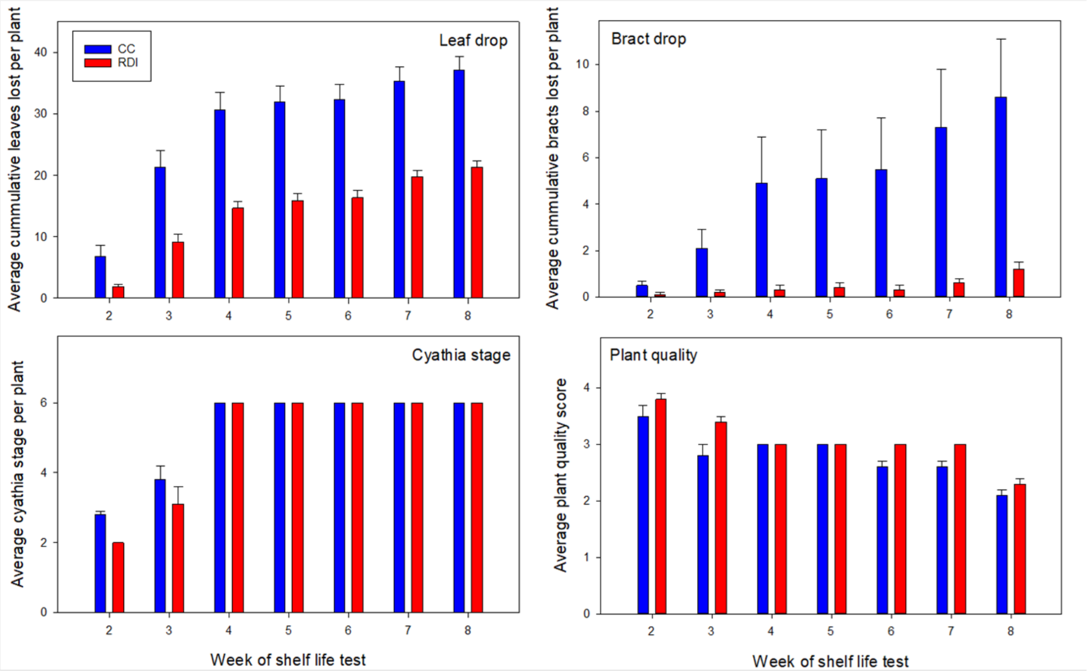


Figure 2.17. Poinsettia quality parameters measured during the shelf-life test at Neame Lea Nursery on Commercial Control plants and those previously treated with RDI. A) average cumulative leaf fall per plant, B) bract fall, C) cyathia stage and D) subjective quality score. Results are means of 12 replicate plants with associated standard errors. Treatment effects on leaf and bract drop were statistically significant from Week 4 (*p*<0.05).

Figure 2.18. The quality of plants from the Commercial Control treatment A) was clearly lower than those plants that had previously been treated with RDI B). Photo taken on 15 January 2020.

Discussion

The experiment at Staplehurst was closely monitored by the NIAB EM team via daily analysis of remote data sets and frequent visits to site to carry out other measurements to support our interpretations. The effects of the RDI treatment on plant physiology were monitored closely over 6 weeks, and the timing and degree of responses triggered by the rootzone water deficits were measured, analysed, and used to adjust the intensity of the RDI treatment in real time.

For RDI to be implemented effectively and consistently, it is necessary to identify how environmental factors that affect plant growth such as air temperature, vapour pressure deficit, light and irrigation water availability vary across the production area. The first and easiest parameter to measure is the performance of the irrigation system; this is best done by carrying out an irrigation system audit to understand system performance and to identify and resolve issues (see Objective 3). The measurements carried out at Staplehurst showed that the uniformity of irrigation within and between benches in different irrigation blocks was good and was sufficient for the experiment to proceed. This exercise highlighted the wetter areas in the middle of some benches where drips from roof vents might raise substrate VMC and reduce the effectiveness of RDI; this scenario can be seen in Figure 2.10A and was apparent in the one of the labelled plants that the Staplehurst team routinely used to measure plant heights – stem extension in this plant was not so effectively controlled by the RDI treatment.

Understanding the variability across the growing area is also important to give confidence that the data sets generated from the sensor bench are representative of the wider crop. Without this reassurance, the severity of RDI / DI applied to the wider crop may not be optimised which would again result in variable results that would impact on grower confidence in the techniques.

The shelf-life tests carried out in Neame Lea’s new facility confirmed our earlier work that prior exposure to an RDI treatment in September/early October could improve tolerance to stresses encountered during distribution, retailing and home life. The mechanistic basis of this priming effect is as yet unknown but could include differential sensitivities to the plant hormones ethylene, abscisic acid and auxin in an interaction that regulates abscission zone activity, or to changes in the plant’s antioxidant status. An extended and assured shelf-life potential would be of great value to growers, retailers and customers, and our results suggest that this could be achieved inexpensively, at least in some varieties, as a beneficial side effect of applying RDI during the exponential growth phase to limit stem extension. Again, further research is needed to identify which varieties would best respond.

The perception and understanding of what Is meant by plant “quality” at dispatch and during shelf- or home life is very variable across the industry since the allocation of various scores is often subjective. The development of more objective quality criteria for eventual use by scientists and growers at dispatch and during shelf-life is needed to properly assess the effects of different growing practices, locations, experimental treatments etc on the quality of named varieties (see Objective 4). Without these, it is impossible to maximise the outputs and knowledge generated from grower trials and more scientific experiments.

AHDB’s decision to fund PO 22 arose from the various discussions at grower meetings in which the outcomes from PO 21 A&B, from our earlier Defra-funded work, and from the “dry growing” regime at Neame Lea instigated in 2016 were questioned by some growers who were concerned about the risks of using RDI and DI as a non-chemical method of growth control. Building grower confidence in the RDI and DI techniques is essential, but this is perhaps best carried out through personal experience gained from trialling these approaches on the nursery. This barrier to uptake should not be underestimated and efforts are needed to tackle this and other reservations if non-chemical growth control is to become the norm. The daily questions and uncertainties of the growing team at Staplehurst during the imposition of the RDI treatment were captured in a word cloud constructed from SMS and WhatsApp messages and conversations over the phone and in person (Figure 2.19A). These concerns are from a growing team with previous experience of using RDI, who knew that real-time data sets were being scrutinised several times a day and who had continuous support from the NIAB EM project team.

Figure 2.19. Comments from the Staplehurst growing team captured A) during the RDI drying episodes and B) following plant recovery following re-wetting events and the end of the RDI treatment.

This perhaps highlights the scale of the challenge ahead in trying to overcome these concerns and barriers to uptake, but equally the comments after plants repeatedly recovered from RDI cycles are encouraging (Figure 2.19B). The growing team at Staplehurst are now far more confident and willing to hold off on irrigating for an extra day or two and are keen to explore how the benefits of RDI can be extended across the nursery and to other pot and bedding crops.

Objective 3: To develop precision and deficit irrigation treatments for the non-chemical growth control of pot bedding crops

Introduction

We have shown that the sensor-based RDI approach can be used effectively as a non-chemical means of growth control in potted poinsettia crops, with additional beneficial effects on plant quality at dispatch and shelf-life potential. These benefits can be achieved in the commercial production of poinsettia, although close monitoring of crop and real-time data is needed until nursery staff become familiar with the technique.

However, in pot and pack bedding, a sensor-based approach to applying precision irrigation and RDI is not appropriate since many moisture sensors require a minimum of 1 L of soil volume surrounding the measurement prongs in order to achieve accurate and precise measurements of substrate moisture content. The relatively small rooting volume in many pot bedding, and all of pack bedding, precludes the use of the majority of sensors, and so an alternative approach is needed.

In PO 21 A&B we showed that in poinsettia, and indeed in all other transpiring plants, the rate of substrate drying is often closely matched to evaporative demand, and that the slope of this relationship could be used to determine whether or not plants receiving an RDI treatment were perceiving a limiting substrate water availability. Since this data could be viewed remotely and in real-time, it could be used to inform researchers' and growers' decision-making. However, the system described above was a sensor-based system, and so an alternative was needed for pot and pack bedding.

The most effective and inexpensive way to estimate plant water loss under different evaporative demands and irrigation treatments is to simply measure plant water loss using an electronic balance – an approach we used in PO 21 A&B. However, as explained above, access to real-time data is needed and so in this project, we planned to use wireless weighing balances that were being developed and supplied by project partner 30 Mhz. Unfortunately, due to pandemic-related and other delays, reliable and accurate balances only became available from November 2022, and so the proposed work programme could not be completed. However, we were able to test the accuracy and reliability of the wireless balances in two different growing scenarios, the first with a potted strawberry crop in a controlled environment (CE) room at NIAB EM, and the second with a crop of primrose at Staplehurst Nurseries. The data sets from this pump priming work will inform our post-project research and exploitation activities in the pot and pack bedding, potted edibles, and soft fruit sectors.

Materials and methods

Selection of pot and pack bedding varieties

Pot bedding species originally selected by the Project Consortium included Senetti, Osteospermum, Dianthus, Geraniums, Dahlias, and Fuchsia. However, the lengthy delays in receiving the balances meant that transpiring crops that were available in November 2022 – January 2023 had to be chosen. At NIAB East Malling, a Malling™ Fruits strawberry variety growing in a CE room was selected, and at Staplehurst Nurseries, a potted crop of primrose was chosen.

Measuring plant water loss

At NIAB East Malling, the 30Mhz wireless balance was placed in a CE room and four Malling strawberry plants in 3 L pots of coir were positioned on the balance (Figure 3.1). Irrigation and fertigation to each pot was supplied *via* two dripper stakes each connected to a 1.2 L h^{-1}, non-return dripper. The timing and duration of irrigation events was controlled using a Galcon DC-4S unit (City Irrigation Ltd, Bromley, UK) connected to a manifold housing a DC-4S ¾" valve for each of the treatments.

Figure 3.1. The 30 MHz wireless balance in a CE room at NIAB EM. Evaporative water loss from four Malling strawberry plants was recorded continuously from 3 November 2022 to 8 February 2023. Photo taken on 9 December 2022. .

Irrigation to the strawberry plants was scheduled using precision irrigation control where changes in CVMC were monitored using Delta-T SM150T sensors (Delta-T Devices Ltd). In each treatment, three sensors were connected to a Delta-T GP2 Advanced Datalogger and Controller unit. The average value from the SM150T sensors was calculated automatically and if the average CVMC value was equal to or less than the irrigation set point, the solenoid valves were opened automatically. The duration of irrigation at each event was adjusted to deliver the target run-off for each treatment. The GP2s were connected in series to a solar-powered Delta-T GPRS modem which allowed remote access for daily monitoring and adjustment of the irrigation set points.

To measure evaporative water loss from the pots and plants, drippers to each of the four pots were removed to allow gradual coir drying. Plants were monitored daily and the point at which leaves began to wilt was noted. The drippers were then replaced and the coir in each pot was returned to pot capacity. A second coir drying and rewetting event was imposed in the same way 3 weeks later.

At Staplehurst Nurseries, the wireless balance was raised above the flood-and-drain bench and eight potted primrose plants were placed upon it (Figure 3.2). From 21 December 2022, evaporative water loss was measured daily up to the point at which plants began to wilt. Nursery staff then rewatered the plants to return the substrate to full capacity and replaced the pots on the balance. This cycle was repeated throughout January and February 2023.

Real-time access to data was available via the 30 MHz gateways installed at each site

Figure 3.2. The 30 MHz wireless balance deployed at Staplehurst Nurseries. Evaporative water loss from eight primrose plants was recorded continuously from 21 December 2022 to 14 February 2023. Photo taken on 21 December 2022. .

Monitoring the phytoclimate

At each site, air temperature and relative humidity were measured every five minutes inside using Delta-T HT2nl-02 RH/Precision Air Temperature Sensors. Data were uploaded onto Delta-T Devices' DeltaLINK Cloud reports and dashboards and were monitored remotely several times each day. Vapour pressure deficit was calculated automatically using preloaded scripts in the GP2 datalogger. The mean VPD value over each hour was calculated, and the sum of the 24 values gave the total daily VPD value.

Calculating crop co-efficients

Crop co-efficients (K_c) were calculated using the following equation:

$$ET_c = ET_o \text{ x } K_c$$

where ET_c is the evaporative weight loss over 24 h, and ET_o is the evaporative demand over 24 h, which, when re-arranged gives:

$$K_c = \frac{ET_c}{ET_o}$$

Results

Strawberry

Daily irrigation events, drainage, and strawberry plant water use were recorded by the balance from 9 November 2022 to 28 February 2023; an example data set is shown in Figure 3.3. On each day, the rapid gain rise in weight caused by the two or three daily irrigation events was quickly followed by a rapid loss of weight which represents drainage through the pots and out of the balance. The subsequent and more gradual weight loss was due to transpirational water loss during the light period which then slowed during the dark period when stomata closed. The gradual rise in weight over the 8-day period was due to fruit expansion; during this time several small green fruit on each of the four plants developed into pink fruit (the stage just before ripe fruit were harvested).

Once irrigation was withheld from the four strawberry plants, weight loss over the following 5 days was recorded (Figure 3.4), and the total weight loss over 24 h was calculated (Table 3.1). The cumulative VPD over the same 24 h was calculated, and the data used to calculate K_c (Table 3.1). This exercise was repeated in February and values of K_c were calculated again (Table 3.1).

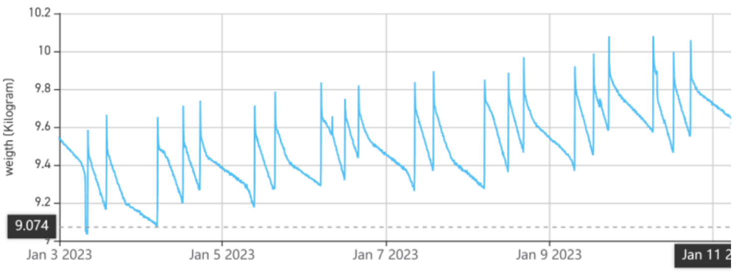


Figure 3.3. Changes in strawberry plant-and-pot weights over an 8-day period in January 2023. Irrigation events, subsequent drainage, and plant evaporative losses over the light and dark periods in the CE room from the four plants on the wireless balance can be clearly seen.

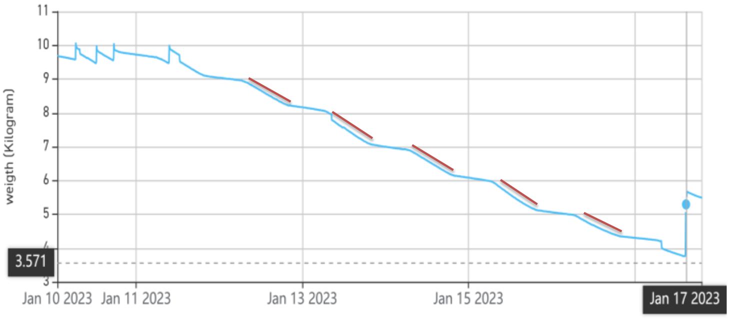


Figure 3.4. Changes in strawberry plant-and-pot weights over an 5-day period after the cessation of irrigation. The deviation on the slope of the rate of change of weight loss on 16 January 2023 indicates that transpirational water loss was limited by stomatal closure induced by the imposed rootzone water deficit.

On both occasions, the calculated mean K_c value for the cropping Malling strawberry variety used in the experiment was similar, 11.14 and 11.40 g water lost / kPa. This K_c value could be used to calculate daily plant water

Table 3.1. Weight loss from transpiring strawberry plants over several days following cessation of irrigation, cumulative VPD values over each 24 h period, and corresponding crop co-efficients. Italicised numbers represent data collected once stomatal closure was triggered.

Date	Total weight loss (kg)	Weight loss per plant (g)	Cumulative VPD over 24 h (kPa)	K_c
12/01/2023	2.16	539.50	18.09	11.40
13/01/2023	1.90	474.06	22.71	11.53
14/01/2023	1.64	410.38	20.51	12.42
15/01/2023	1.40	348.94	26.72	9.20
16/01/2023	1.17	292.69	27.11	8.30
17/01/2023	0.05	14.75	28.11	0.52
04/02/2023	1.00	251.00	19.89	12.62
05/02/2023	1.02	255.75	21.86	11.70
06/02/2023	0.98	244.50	21.84	11.19
07/02/2023	0.88	220.75	21.85	10.10
08/02/2023	0.45	111.75	22.11	5.05

loss during the cropping stage under variable VPD values, which in turn could inform the scheduling of precision irrigation and/or the imposition of RDI to a crop of this strawberry variety. Once the relationship between plant water loss and VPD is uncoupled by stomatal closure (see italicised value sin Table 3.1), the resulting crop-coefficient is unreliable and should not be used.

The rate of change of weight loss over the photoperiod can also provide information about whether the imposed substrate water deficit is severe enough to elicit a physiological response. A deviation in the rate of change in weight loss over the photoperiod, most easily visualised by a change in the slope, indicates when transpirational water loss is slowed due to progressive stomatal closure. This change in slope was obvious between 15 and 16 January 2023 (Figure 3.4), and two of the four plants began to wilt on16 January 2023 (Figure 3.5).

Figure 3.5. After 6 days without irrigation, two of the four strawberry plants on the wireless balance began to wilt. Photo taken on 17 January 2023.

Primrose

The eight primrose plants on the balance were removed from the flood-and-drain irrigation system and so were irrigated by hand when nursery staff deemed it necessary. From 1 January 2023 to 12 February 2023 plants were irrigated three times, and between these irrigation events, plants were allowed to dry and daily weight loss was recorded by the balance (Figure 3.6). Small but significant rises in plant-and-pot weights occurred on two occasions (indicated by the orange arrows) and so the periods over which K_c values were estimated (indicated by the black horizontal lines) were chosen to avoid these days.

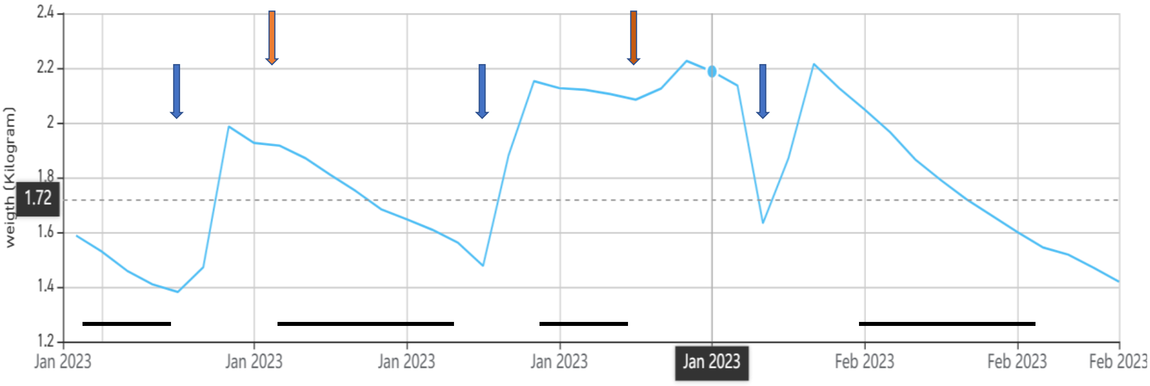


Figure 3.6. Changes in primrose plant-and-pot weights over from 1 January to 12 February 2023. Irrigation events and plant evaporative losses over the light and dark periods in the glasshouse from the eight plants on the wireless balance can be clearly seen. Blue arrows represent irrigation events, orange arrows indicate where plants gained water from an unknown source.

As expected, values of daily cumulative VPD were much more variable in the glasshouse than in the CE room, and so the corresponding daily evaporative weight loss varied too (Figure 3.6 A&B). There was a reasonable correlation (0.62) between cumulative VPD and pot-and-plant water loss (Figure 3.7) and so crop co-efficients were calculated for each period between irrigation events (Table 3.2). K_c values decreased over the 6-week experiment from 1.92 to 1.52 g water lost/kPa.

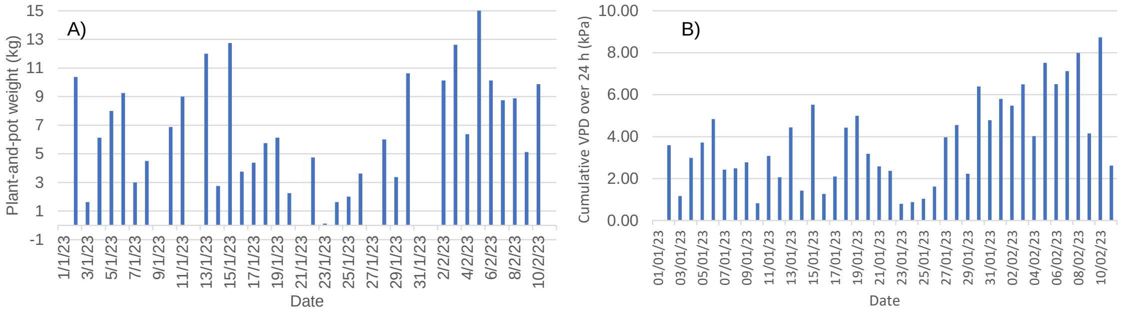


Figure 3.7. A) Daily mean plant and pot water loss and B) daily cumulative VPD in the primrose glass house from 1 January to 12 February 2023).

Discussion

Using the approach described above, the crop co-efficient for the Malling strawberry variety used in this experiment was similar when calculated on two separate occasions 2 weeks apart and could be used to calculate the cumulative water loss over several days so that irrigation could be scheduled to match demand with supply in cropping plants. Further work is needed to calculate Kc values at each stage of plant and crop development (see below), and previous work carried out at East Malling in Defra-funded research showed that KC values needed to be calculated at least twice per week to avoid inadvertently imposing a water deficit stress, and that K_c values rose sharply once fruit entered the rate of rapid expansion at the small green fruit stage.

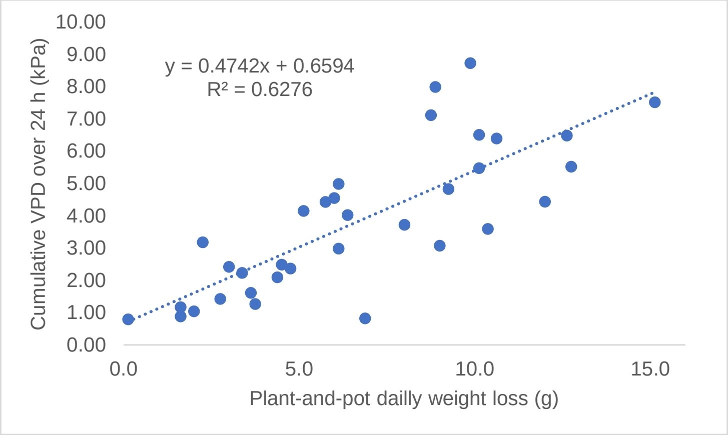


Figure 3.8. Correlation between pot-and-plant weight loss over 24 h and the corresponding cumulative VPD over the same time.

The relatively consistent environmental conditions in the CE room meant that evaporative water loss from the Malling strawberry plants was similar over each 24 h period, until the point at which stomatal closure was triggered by the increasing substrate water deficit. This response is reflected in the change in the slope of weight loss over time and could be used by researchers and growers to identify remotely when plants first begin to perceive a substrate water deficit stress. This approach could be used to inform the imposition of RDI to commercial pot and pack bedding crops on commercial nurseries, and the feasibility of this approach will be tested in post-project work at NIAB East Malling, Staplehurst Nurseries and at Neame Lea Nursery (see below).

Table 3.2. Weight loss from transpiring primrose plants over several days measured in between irrigation events, cumulative VPD values over each 24 h period, and corresponding crop co-efficients.

Date	Total weight loss (kg)	Weight loss per plant (g)	Cumulative VPD over 24 h (kPa)	K_c
02/01/2023	0.083	10.4	3.59	2.89
03/01/2023	0.013	1.6	1.17	1.39
04/01/2023	0.049	6.1	2.99	2.05
05/01/2023	0.064	8.0	3.72	2.15
06/01/2023	0.074	9.3	4.83	1.91
07/01/2023	0.024	3.0	2.42	1.24
08/01/2023	0.036	4.5	2.49	1.81
13/01/2023	0.096	12.0	4.44	2.70
14/01/2023	0.022	2.8	1.43	1.93
15/01/2023	0.102	12.8	5.52	2.31
16/01/2023	0.03	3.8	1.26	2.97
17/01/2023	0.035	4.4	2.10	2.09
18/01/2023	0.046	5.8	4.43	1.30
19/01/2023	0.049	6.1	4.99	1.23
20/01/2023	0.018	2.3	3.18	0.71
22/01/2023	0.038	4.8	2.37	2.01
23/01/2023	0.001	0.1	0.79	0.16
24/01/2023	0.013	1.6	0.88	1.84
25/01/2023	0.016	2.0	1.04	1.92
26/01/2023	0.029	3.6	1.62	2.24
02/02/2023	0.081	10.1	5.47	1.85
03/02/2023	0.101	12.6	6.49	1.95
04/02/2023	0.051	6.4	4.02	1.59
05/02/2023	0.121	15.1	7.52	2.01
06/02/2023	0.081	10.1	6.51	1.56
07/02/2023	0.07	8.8	7.12	1.23
08/02/2023	0.071	8.9	7.99	1.11
09/02/2023	0.041	5.1	4.15	1.23
10/02/2023	0.079	9.9	8.73	1.13
02/02/2023	0.081	10.1	5.47	1.85
03/02/2023	0.101	12.6	6.49	1.95

Deriving K_c values for primrose was more challenging in a commercial glasshouse environment where unexplained increases in pot-and-plant weights in between irrigation events necessitated careful screening of the data to ensure that the calculated K_c values were accurate. Nevertheless, this approach enabled K_c values to be estimated in real time; that values of K_c declined as the plants transitioned from the vegetative to flowering stage was likely due to the fact that flowers have few, if any, stomata, and so whole-plant transpiration rates tend to fall as plants reach maturity. The slower rate of water loss from the smaller primrose plants was reflected in the lower K_c values compared to those for strawberry. Again, the calculated K_c values could be used in conjunction with cumulative daily VPD values to schedule irrigation to commercial crops of primrose.

Post-project activities

The wireless balance at East Malling will be used in conjunction with Linear Variable Displacement Transducers (LVDTs) in further experiments in a new Defra Farming Innovation Programme project to determine the relative sensitivities of stomatal conductance and fruit expansion rate to imposed coir drying events in Malling™ Champion grown in a Total Controlled Environment Agriculture (TCEA) system. This data will then guide the imposition of RDI strategies to try to limit canopy area and evaporational water loss whilst improving aspects of berry quality without reducing fruit size/fresh weight and, therefore, Class 1 yields.

The balance at Staplehurst Nurseries is now being used to calculate weekly K_c values for a Geranium crop (Figure 3.9) so that irrigation can be scheduled more effectively and efficiently. The feasibility of using the combined K_c-VPD approach to identify deviations in the rate of change of weight loss over the photoperiod that would indicate when the crop is beginning to perceive a rootzone water deficit and an irrigation event is needed will also be tested.

Figure 3.9. A geranium crop on the 30 MHz wireless balance deployed at Staplehurst Nurseries. Photo taken on 2 March 2023.

Two balances were installed at Neame Lea Nursery in March 2023, one in a crop of Geranium and the other in a crop of 'New Guinea Impatiens (Figure 3.10). Initially, the derived K_c values will help to inform irrigation scheduling decisions, and later the system will be used to impose and monitor RDI strategies to try to improve crop resilience and improve shelf-life potential. Results from these post-project experiments will be reported at Knowledge exchange days held for the soft fruit sector at NIAB East Malling and at the annual BPOA event.

Figure 3.10. An Impatiens crop on the 30 MHz wireless balance deployed at Neame Lea Nursery. Photo taken on 13 March 2023.

Objective 4: To develop technologies, tools, and approaches to deliver Precision Irrigation in capillary matting growing systems.

Introduction

To date, most sensor-led approaches have been developed for bench ebb-and-flood systems where irrigation is often uniform, and so the variability of pot-to pot-moisture content is low. Capillary matting is viewed as a less expensive alternative method for irrigation control, but variability in pot-to-pot moisture content can be higher. Furthermore, infrastructural factors such as draughts, leaks, “dead” areas, and shaded areas lead to pot-to-pot variation in moisture content in most glasshouse growing systems. However, the uptake of moisture on capillary matting can also be influenced by factors such as the contact between the pot and the matting (pot moulding needs to be “true”), the quality and age of the matting, the installation of the matting (including levelling of the floor), and the ability of the substrate to take up moisture through capillary draw and redistribute it evenly within the pot; the latter is itself influenced by the evenness of substrate volume from pot to pot.

To map and quantify these potential sources of variability in a commercial nursery, Multiple “spot” measurements of moisture content were made in potted poinsettia on capillary matting on benches (Nursery #1) or on the floor (Nursery #2). At the latter site, following a review of the initial data sets, the grower decided to implement four different approaches to try to improve homogeneity within the growing bays. The data sets from each site were then used to decide whether the potential for individual pot variations would permit or limit a sensor-based approach to irrigation management and the imposition of RDI with capillary matting systems.

Materials and methods

Sampling methodology / approach

To investigate the extent and degree of variability in substrate VMC on each nursery, the growing area was split into different sampling areas. The construction of most nurseries (*e.g.,* layout and infrastructure) allows for large growing areas to be logically broken into smaller, similarly sized, sampling areas. This subsequently allows for a more detailed examination of variation across an area, and the specific plants/pots selected for measurement were distributed evenly over each area.

In every case, pots on the edge of the growing area were avoided, but in some cases, it was necessary to sample pots in the second row to avoid damaging plants by walking within the growing crop. When measurements were taken over several days, different sample pots were chosen. At each nursery, measurements were made on the same variety of poinsettia, potted on the same date, and in the same growing media (unless stated otherwise).

To better understand the potential effect of time of watering, an attempt was made to sample substrate VMC at different times during the day in relation to irrigation events. However, commercial operations sometimes had to take precedent over our sampling protocol.

Measurement of substrate moisture content

Substrate VMC was recorded using a hand-held Bluelab Pulse Meter. This device records data and allows it to be exported into Excel. The data was then plotted as "heat maps" onto illustrative glasshouse plans to indicate variation within a bay / house.

Nursery Background information (growing areas)

Nursery #1: on-bench capillary matting

Capillary matting was constructed (top down) as follows:

- Perforated plastic
- Capillary matting
- Impermeable plastic
- Polystyrene (to help level)
- Metal benching

Essentially, there were eight sets of benching, laid in pairs around a path, with each pair labelled as, for example, Bay 1 left hand side (LHS) and Bay 1 right hand side (RHS). Each bench was 1.5m by 27m. Fifty-four substrate moisture measurements were taken from different pots throughout the length of each of the eight sets of benching. The timing of visits meant that moisture content was recorded 1 h (on 16-10-22), 72 h (on 14-10-22), and 120 h (on 16-10-22) after an irrigation event. The first moisture content recorded was 72 h since water, two days later we recorded 120 h since water, then irrigated, allowed to equilibrate and 1 h since water subsequently recorded. The test crop was poinsettia "Christmas Feelings", 10cm pots, potted week 31, 8.5 plants/m2.

Nursery #2: on-floor capillary matting

The on-floor capillary matting was constructed (top down) as follows:

- Perforated plastic
- Capillary matting
- Impermeable plastic
- Sand (to aid levelling)
- Soil

There were eight sets of growing bays, laid in pairs around a path, and labelled, for example, Bay 1 left hand side (LHS) and Bay 1 right hand side (RHS). Each side was approximately 2.5m x 50m. Due to the size of the areas, and of the plants, only pots in the RHS area were sampled, and only the second row of plants were accessible (access to the majority of the crop was not possible. On 30-9-19, 27 sample measurements were taken along the bay 1 h after an irrigation event due to time constraints, but 54 measurements were taken from pots 24 h (1-10-19) and 48 h (30-9-19) after irrigation. The first moisture content recorded was 48 h since water, pots were then irrigated, allowed to equilibrate, and 1 h since water subsequently recorded, one day later we recorded 24 h since water. The test crop was poinsettia "Astro Red" (both years), 1 litre (13cm) pots (both years), potted week 27 (2019) and week 31 (2020), 10.5 plants/m2 (both years).

Interventions made at Nursery #2

Three interventions were made to try to improve the uniformity of irrigation supply across the growing bays. On 21/10/20 3 bays of each intervention were sampled with 54 moisture values recorded per bay. In each case, areas containing the same variety of poinsettia, potted in the same substrate (with the exception of the double matting intervention) and on the same date as the original bays were chosen where possible to facilitate meaningful comparisons:

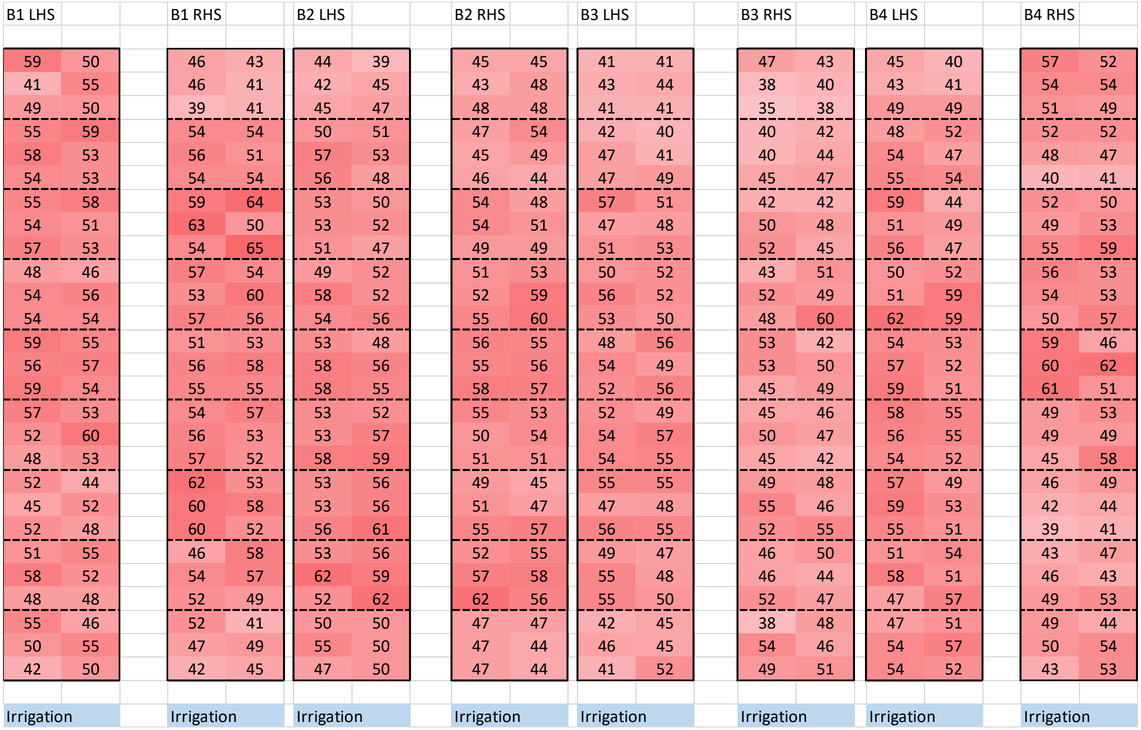
1) The irrigation header pipe was moved to the other end of the house in five bays;
2) Two layers of capillary matting were laid down in three bays - the substrate in these bays was different that in the original measurements;
3) Used capillary matting (2 years old) was laid down in four bays;
4) New capillary matting (first year of use) was laid down in four bays.

Results and Discussion

Nursery #1 – bench capillary matting

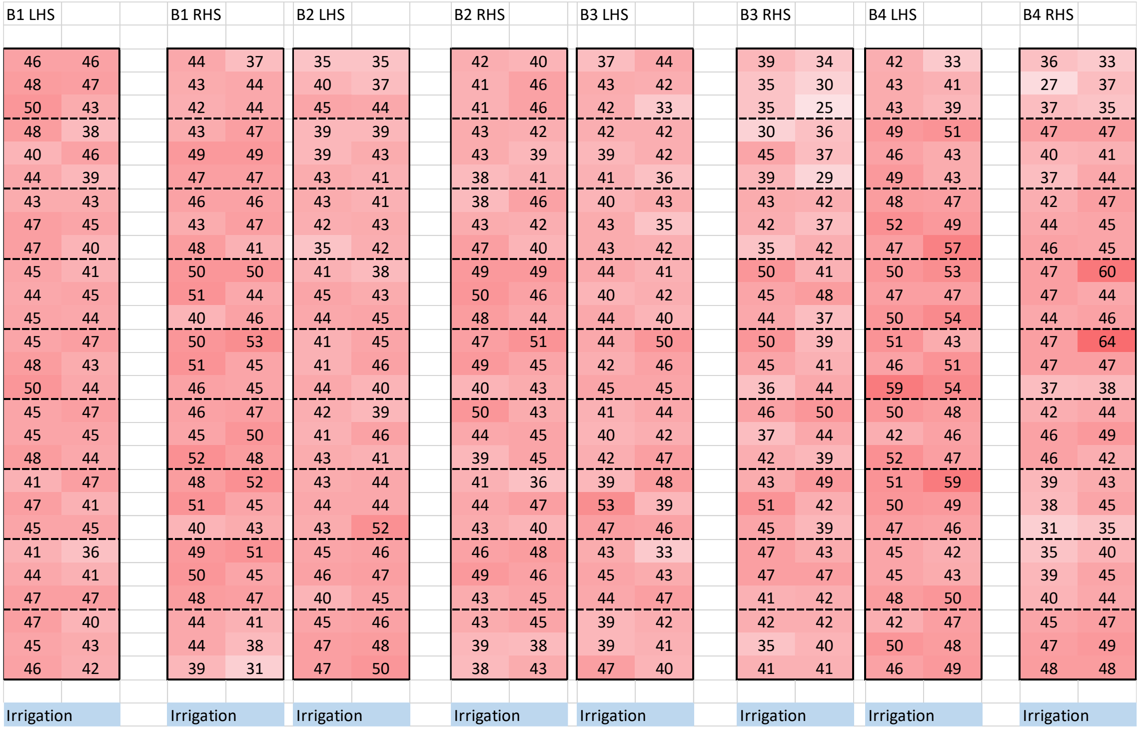
When sampled 1 h after an irrigation event, substrate VMC values were generally uniform over the growing area, (Figure 4.1A), although there were two areas in the house where values were lower. The first was in the bottom left-hand corner centred on Bay 1 RHS and Bay 2 LHS, which was perhaps caused by proximity to the door and the resulting draught), and the second area was on the top edge centred on Bay 2 RHS, Bay 3 LHS and Bay 3 RHS. The latter was, perhaps, caused by increased airflow across the end of the benching.

A similar pattern was noted when moisture contents were measured 72 h after an irrigation event (Figure 4.1B), although the rate of substrate drying was perhaps lower in the middle of the bay, centred on Bay 4 LHS. One hundred and twenty hours after an irrigation event, pot moisture content was again fairly even (Figure 4.1C), although values in Bay 1 LHS were slightly higher.



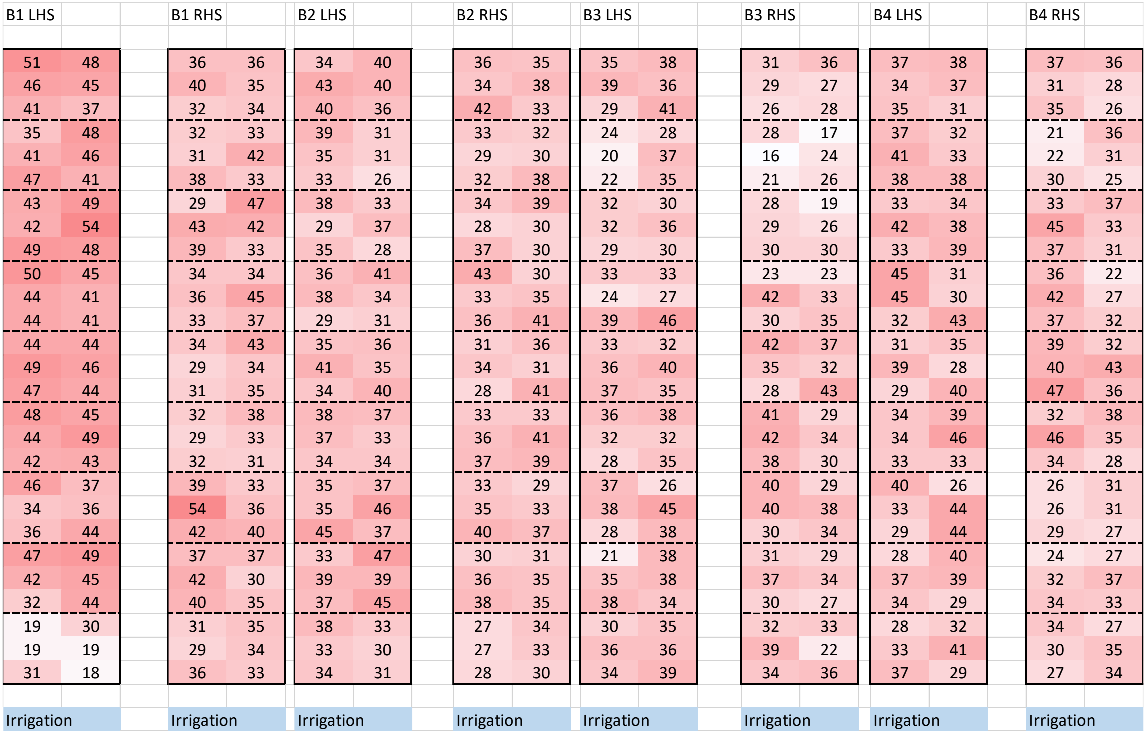
B1 LHS		B1 RHS		B2 LHS		B2 RHS		B3 LHS		B3 RHS		B4 LHS		B4 RHS	
59	50	46	43	44	39	45	45	41	41	47	43	45	40	57	52
41	55	46	41	42	45	43	48	43	44	38	40	43	41	54	54
49	50	39	41	45	47	48	48	41	41	35	38	49	49	51	49
55	59	54	54	50	51	47	54	42	40	40	42	48	52	52	52
58	53	56	51	57	53	45	49	47	41	40	44	54	47	48	47
54	53	54	54	56	48	46	44	47	49	45	47	55	54	40	41
55	58	59	64	53	50	54	48	57	51	42	42	59	44	52	50
54	51	63	50	53	52	54	51	47	48	50	48	51	49	49	53
57	53	54	65	51	47	49	49	51	53	52	45	56	47	55	59
48	46	57	54	49	52	51	53	50	52	43	51	50	52	56	53
54	56	53	60	58	52	52	59	56	52	52	49	51	59	54	53
54	54	57	56	54	56	55	60	53	50	48	60	62	59	50	57
59	55	51	53	53	48	56	55	48	56	53	42	54	53	59	46
56	57	56	58	58	56	55	56	54	49	53	50	57	52	60	62
59	54	55	55	58	55	58	57	52	56	45	49	59	51	61	51
57	53	54	57	53	52	55	53	52	49	45	46	58	55	49	53
52	60	56	53	53	57	50	54	54	57	50	47	56	55	49	49
48	53	57	52	58	59	51	51	54	55	45	42	54	52	45	58
52	44	62	53	53	56	49	45	55	55	49	48	57	49	46	49
45	52	60	58	53	56	51	47	47	48	55	46	59	53	42	44
52	48	60	52	56	61	55	57	56	55	52	55	55	51	39	41
51	55	46	58	53	56	52	55	49	47	46	50	51	54	43	47
58	52	54	57	62	59	57	58	55	48	46	44	58	51	46	43
48	48	52	49	52	62	62	56	55	50	52	47	47	57	49	53
55	46	52	41	50	50	47	47	42	45	38	48	47	51	49	44
50	55	47	49	55	50	47	44	46	45	54	46	54	57	50	54
42	50	42	45	47	50	47	44	41	52	49	51	54	52	43	53
Irrigation		Irrigation		Irrigation		Irrigation		Irrigation		Irrigation		Irrigation		Irrigation	

Figure 4.1 A). Substrate VMC (%) values taken 1 h after an irrigation event at different places across the growing area (capillary matting on benches) at Nursery #1. Values are displayed as a "heat map" and each bay is labelled as described with "B1 LHS" representing Bay 1 Left-hand Side; the "Irrigation" label shows the position of the header pipes.



B1 LHS		B1 RHS		B2 LHS		B2 RHS		B3 LHS		B3 RHS		B4 LHS		B4 RHS	
46	46	44	37	35	35	42	40	37	44	39	34	42	33	36	33
48	47	43	44	40	37	41	46	43	42	35	30	43	41	27	37
50	43	42	44	45	44	41	46	42	33	35	25	43	39	37	35
48	38	43	47	39	39	43	42	42	42	30	36	49	51	47	47
40	46	49	49	39	43	43	39	39	42	45	37	46	43	40	41
44	39	47	47	43	41	38	41	41	36	39	29	49	43	37	44
43	43	46	46	43	41	38	46	40	43	43	42	48	47	42	47
47	45	43	47	42	43	43	42	43	35	42	37	52	49	44	45
47	40	48	41	35	42	47	40	43	42	35	42	47	57	46	45
45	41	50	50	41	38	49	49	44	41	50	41	50	53	47	60
44	45	51	44	45	43	50	46	40	42	45	48	47	47	47	44
45	44	40	46	44	45	48	44	44	40	44	37	50	54	44	46
45	47	50	53	41	45	47	51	44	50	50	39	51	43	47	64
48	43	51	45	41	46	49	45	42	46	45	41	46	51	47	47
50	44	46	45	44	40	40	43	45	45	36	44	59	54	37	38
45	47	46	47	42	39	50	43	41	44	46	50	50	48	42	44
45	45	45	50	41	46	44	45	40	42	37	44	42	46	46	49
48	44	52	48	43	41	39	45	42	47	42	39	52	47	46	42
41	47	48	52	43	44	41	36	39	48	43	49	51	59	39	43
47	41	51	45	44	44	44	47	53	39	51	42	50	49	38	45
45	45	40	43	43	52	43	40	47	46	45	39	47	46	31	35
41	36	49	51	45	46	46	48	43	33	47	43	45	42	35	40
44	41	50	45	46	47	49	46	45	43	47	47	45	43	39	45
47	47	48	47	40	45	43	45	44	47	41	42	48	50	40	44
47	40	44	41	45	46	43	45	39	42	42	42	42	47	45	47
45	43	44	38	47	48	39	38	39	41	35	40	50	48	47	49
46	42	39	31	47	50	38	43	47	40	41	41	46	49	48	48
Irrigation		Irrigation		Irrigation		Irrigation		Irrigation		Irrigation		Irrigation		Irrigation	

Figure 4.1 B). A "heat" map of substrate VMC (%) values taken 72 h after an irrigation event at different places across the growing area (capillary matting on benches) at Nursery #1.



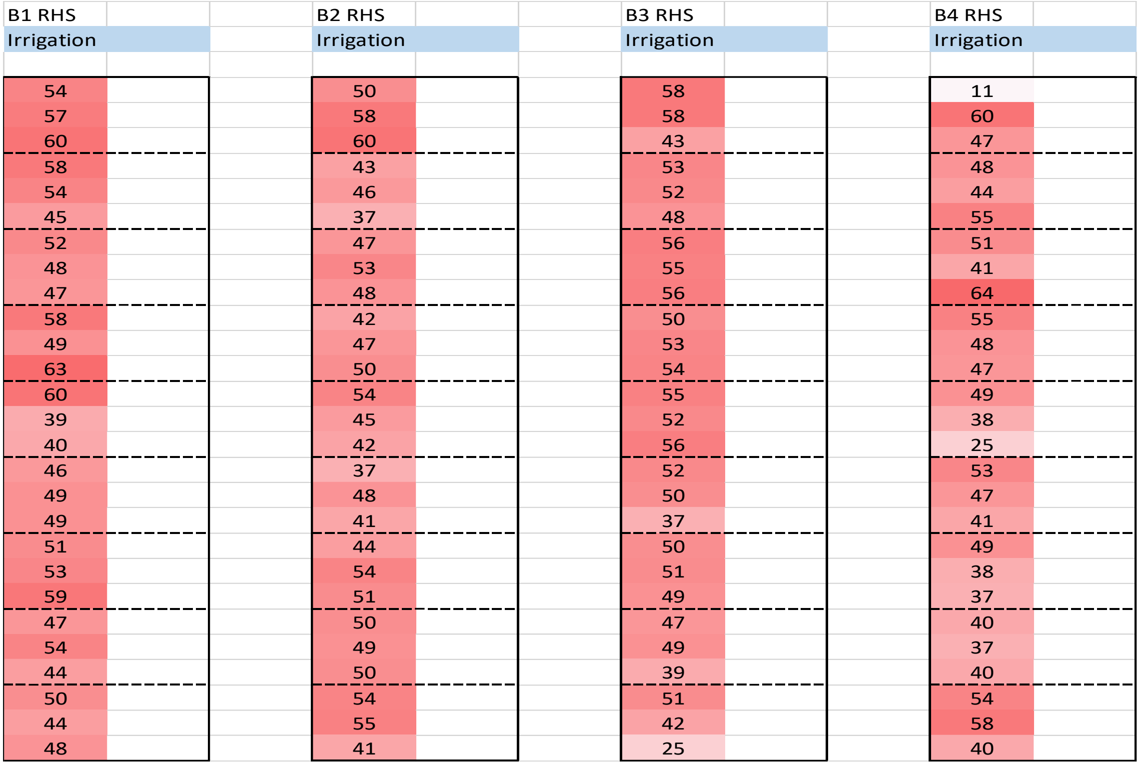
B1 LHS		B1 RHS		B2 LHS		B2 RHS		B3 LHS		B3 RHS		B4 LHS		B4 RHS	
51	48	36	36	34	40	36	35	35	38	31	36	37	38	37	36
46	45	40	35	43	40	34	38	39	36	29	27	34	37	31	28
41	37	32	34	40	36	42	33	29	41	26	28	35	31	35	26
35	48	32	33	39	31	33	32	24	28	28	17	37	32	21	36
41	46	31	42	35	31	29	30	20	37	16	24	41	33	22	31
47	41	38	33	33	26	32	38	22	35	21	26	38	38	30	25
43	49	29	47	38	33	34	39	32	30	28	19	33	34	33	37
42	54	43	42	29	37	28	30	32	36	29	26	42	38	45	33
49	48	39	33	35	28	37	30	29	30	30	30	33	39	37	31
50	45	34	34	36	41	43	30	33	33	23	23	45	31	36	22
44	41	36	45	38	34	33	35	24	27	42	33	45	30	42	27
44	41	33	37	29	31	36	41	39	46	30	35	32	43	37	32
44	44	34	43	35	36	31	36	33	32	42	37	31	35	39	32
49	46	29	34	41	35	34	31	36	40	35	32	39	28	40	43
47	44	31	35	34	40	28	41	37	35	28	43	29	40	47	36
48	45	32	38	38	37	33	33	36	38	41	29	34	39	32	38
44	49	29	33	37	33	36	41	32	32	42	34	34	46	46	35
42	43	32	31	34	34	37	39	28	35	38	30	33	33	34	28
46	37	39	33	35	37	33	29	37	26	40	29	40	26	26	31
34	36	54	36	35	46	35	33	38	45	40	38	33	44	26	31
36	44	42	40	45	37	40	37	28	38	30	34	29	44	29	27
47	49	37	37	33	47	30	31	21	38	31	29	28	40	24	27
42	45	42	30	39	39	36	35	35	38	37	34	37	39	32	37
32	44	40	35	37	45	38	35	38	34	30	27	34	29	34	33
19	30	31	35	38	33	27	34	30	35	32	33	28	32	34	27
19	19	29	34	33	30	27	33	36	36	39	22	33	41	30	35
31	18	36	33	34	31	28	30	34	39	34	36	37	29	27	34
Irrigation		Irrigation		Irrigation		Irrigation		Irrigation		Irrigation		Irrigation		Irrigation	

Figure 4.1 C). A “heat” map of substrate VMC (%) values taken 120 h after an irrigation event at different places across the growing area (capillary matting on benches) at Nursery #1.

Nursery #2 - floor capillary matting

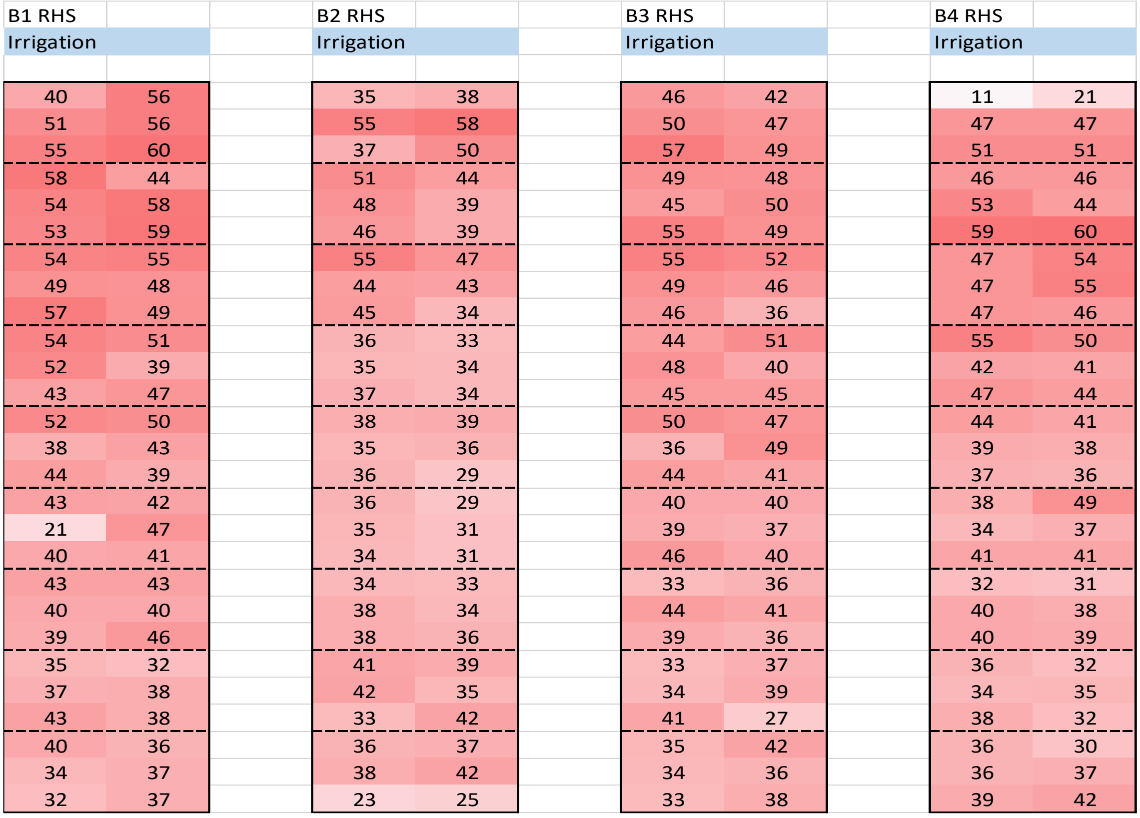
Variability in pot substrate VMC values measured 1 h after an irrigation event was higher than that detected on the bench growing system, Values of substrate VMC in pots at the end of the bay furthest from the irrigation were a little lower than elsewhere (Figure 4.2A), suggesting that the irrigation water didn’t spread along the capillary matting far enough during the irrigation period. Staff at Nursery#1 confirmed that they often had to “spot” water that end of the bays to correct this. Substrate VMC values in plants sited in in Bay 4 were generally lower than in other areas, suggesting that irrigation supply to this area was not optimised (Figure 4.2A).

Similar differences were detected 24 and 48 h after the irrigation event (Figure 4.2B&C). After 1 day, plants in the end of the bay furthest from the irrigation were growing a little drier, and after 2 days, substrate VMC values in pots sited in Bays 2 and 4 were much lower than in Bays 1 and 3. Overall, irrigation supply was higher to the plants nearest the irrigation pipework.



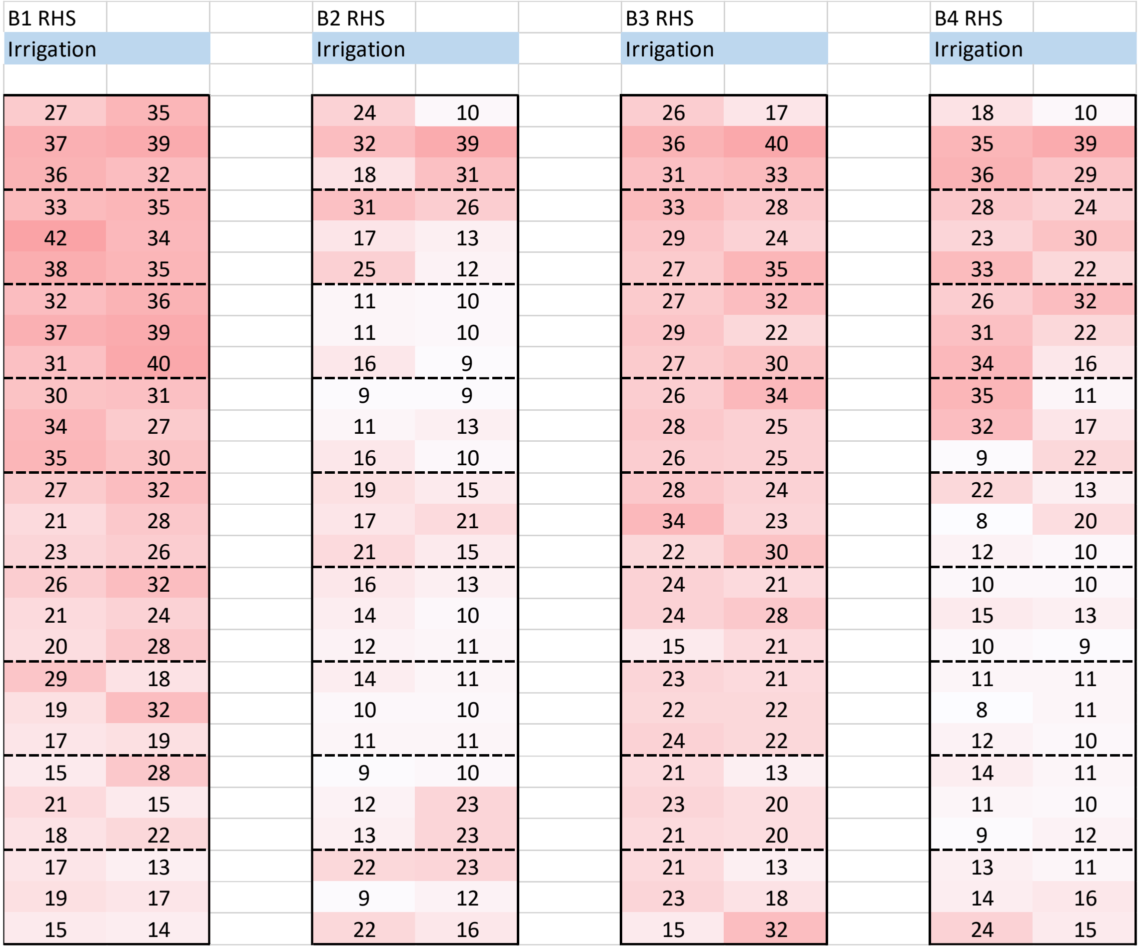
B1 RHS		B2 RHS		B3 RHS		B4 RHS	
Irrigation		Irrigation		Irrigation		Irrigation	
54		50		58		11	
57		58		58		60	
60		60		43		47	
58		43		53		48	
54		46		52		44	
45		37		48		55	
52		47		56		51	
48		53		55		41	
47		48		56		64	
58		42		50		55	
49		47		53		48	
63		50		54		47	
60		54		55		49	
39		45		52		38	
40		42		56		25	
46		37		52		53	
49		48		50		47	
49		41		37		41	
51		44		50		49	
53		54		51		38	
59		51		49		37	
47		50		47		40	
54		49		49		37	
44		50		39		40	
50		54		51		54	
44		55		42		58	
48		41		25		40	

Figure 4.2 A). Substrate VMC (%) values taken 1 h after an irrigation event at different places across the growing area (capillary matting on the floor) at Nursery #2. Values are displayed as a "heat map" and each bay is labelled as described with "B1 RHS" representing Bay 1 Right-hand Side; the "Irrigation" label shows the position of the header pipes.



B1 RHS		B2 RHS		B3 RHS		B4 RHS	
Irrigation		Irrigation		Irrigation		Irrigation	
40	56	35	38	46	42	11	21
51	56	55	58	50	47	47	47
55	60	37	50	57	49	51	51
58	44	51	44	49	48	46	46
54	58	48	39	45	50	53	44
53	59	46	39	55	49	59	60
54	55	55	47	55	52	47	54
49	48	44	43	49	46	47	55
57	49	45	34	46	36	47	46
54	51	36	33	44	51	55	50
52	39	35	34	48	40	42	41
43	47	37	34	45	45	47	44
52	50	38	39	50	47	44	41
38	43	35	36	36	49	39	38
44	39	36	29	44	41	37	36
43	42	36	29	40	40	38	49
21	47	35	31	39	37	34	37
40	41	34	31	46	40	41	41
43	43	34	33	33	36	32	31
40	40	38	34	44	41	40	38
39	46	38	36	39	36	40	39
35	32	41	39	33	37	36	32
37	38	42	35	34	39	34	35
43	38	33	42	41	27	38	32
40	36	36	37	35	42	36	30
34	37	38	42	34	36	36	37
32	37	23	25	33	38	39	42

Figure 4.2 B). A "heat" map of substrate VMC (%) values taken 24 h after an irrigation event at different places across the growing area (capillary matting on the floor) at Nursery #2.



B1 RHS		B2 RHS		B3 RHS		B4 RHS	
Irrigation		Irrigation		Irrigation		Irrigation	
27	35	24	10	26	17	18	10
37	39	32	39	36	40	35	39
36	32	18	31	31	33	36	29
33	35	31	26	33	28	28	24
42	34	17	13	29	24	23	30
38	35	25	12	27	35	33	22
32	36	11	10	27	32	26	32
37	39	11	10	29	22	31	22
31	40	16	9	27	30	34	16
30	31	9	9	26	34	35	11
34	27	11	13	28	25	32	17
35	30	16	10	26	25	9	22
27	32	19	15	28	24	22	13
21	28	17	21	34	23	8	20
23	26	21	15	22	30	12	10
26	32	16	13	24	21	10	10
21	24	14	10	24	28	15	13
20	28	12	11	15	21	10	9
29	18	14	11	23	21	11	11
19	32	10	10	22	22	8	11
17	19	11	11	24	22	12	10
15	28	9	10	21	13	14	11
21	15	12	23	23	20	11	10
18	22	13	23	21	20	9	12
17	13	22	23	21	13	13	11
19	17	9	12	23	18	14	16
15	14	22	16	15	32	24	15

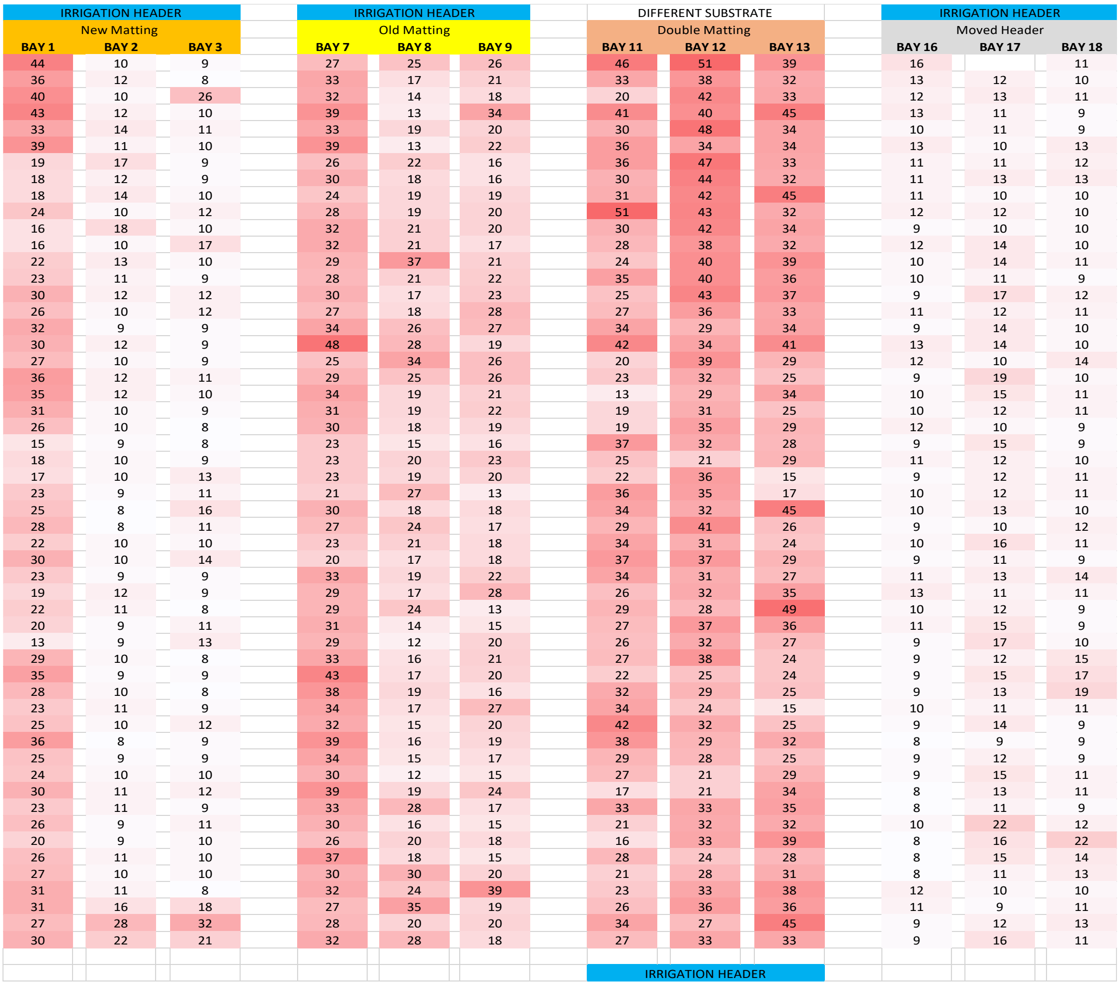
Figure 4.2 C). A "heat" map of substrate VMC (%) values taken 48 h after an irrigation event at different places across the growing area (capillary matting on the floor) at Nursery #2.

<u>Nursery #2 – effects of the interventions</u>

Moving the irrigation header pipe resulted in lower substrate VMC values in Bays 16-18 when measurements were made 48 h after an irrigation event (Figure 4.3), and values were relatively consistent across the bays.

Values of moisture content in pots on the double matting, albeit in a different substrate, were generally higher in all three bays (11, 12 and 13), and were highest at the end furthest away from the irrigation header pipe (Figure 4.3), probably due to the remedial "spot" watering that was routinely applied there. Areas of low substrate moisture content were also detected along the bay.

On the old capillary matting, substrate VMC values in Bay 7 were generally higher, and were fairly consistent in Bays 8 and 9, again with the exception of the "spot" watering effect at the end furthest from the irrigation header pipework (Figure 4.3). In bays with the new capillary matting, substrate VMC values were again generally higher in Bay 1 as in the original measurements, but more consistent in Bays 2 and 3, with the effect of the “spot” watering noted again (Figure 4.3).



IRRIGATION HEADER			IRRIGATION HEADER			DIFFERENT SUBSTRATE			IRRIGATION HEADER		
New Matting			Old Matting			Double Matting			Moved Header		
BAY 1	**BAY 2**	**BAY 3**	**BAY 7**	**BAY 8**	**BAY 9**	**BAY 11**	**BAY 12**	**BAY 13**	**BAY 16**	**BAY 17**	**BAY 18**
44	10	9	27	25	26	46	51	39	16		11
36	12	8	33	17	21	33	38	32	13	12	10
40	10	26	32	14	18	20	42	33	12	13	11
43	12	10	39	13	34	41	40	45	13	11	9
33	14	11	33	19	20	30	48	34	10	11	9
39	11	10	39	13	22	36	34	34	13	10	13
19	17	9	26	22	16	36	47	33	11	11	12
18	12	9	30	18	16	30	44	32	11	13	13
18	14	10	24	19	19	31	42	45	11	10	10
24	10	12	28	19	20	51	43	32	12	12	10
16	18	10	32	21	20	30	42	34	9	10	10
16	10	17	32	21	17	28	38	32	12	14	10
22	13	10	29	37	21	24	40	39	10	14	11
23	11	9	28	21	22	35	40	36	10	11	9
30	12	12	30	17	23	25	43	37	9	17	12
26	10	12	27	18	28	27	36	33	11	12	11
32	9	9	34	26	27	34	29	34	9	14	10
30	12	9	48	28	19	42	34	41	13	14	10
27	10	9	25	34	26	20	39	29	12	10	14
36	12	11	29	25	26	23	32	25	9	19	10
35	12	10	34	19	21	13	29	34	10	15	11
31	10	9	31	19	22	19	31	25	10	12	11
26	10	8	30	18	19	19	35	29	12	10	9
15	9	8	23	15	16	37	32	28	9	15	9
18	10	9	23	20	23	25	21	29	11	12	10
17	10	13	23	19	20	22	36	15	9	12	11
23	9	11	21	27	13	36	35	17	10	12	11
25	8	16	30	18	18	34	32	45	10	13	10
28	8	11	27	24	17	29	41	26	9	10	12
22	10	10	23	21	18	34	31	24	10	16	11
30	10	14	20	17	18	37	37	29	9	11	9
23	9	9	33	19	22	34	31	27	11	13	14
19	12	9	29	17	28	26	32	35	13	11	11
22	11	8	29	24	13	29	28	49	10	12	9
20	9	11	31	14	15	27	37	36	11	15	9
13	9	13	29	12	20	26	32	27	9	17	10
29	10	8	33	16	21	27	38	24	9	12	15
35	9	9	43	17	20	22	25	24	9	15	17
28	10	8	38	19	16	32	29	25	9	13	19
23	11	9	34	17	27	34	24	15	10	11	11
25	10	12	32	15	20	42	32	25	9	14	9
36	8	9	39	16	19	38	29	32	8	9	9
25	9	9	34	15	17	29	28	25	9	12	9
24	10	10	30	12	15	27	21	29	9	15	11
30	11	12	39	19	24	17	21	34	8	13	11
23	11	9	33	28	17	33	33	35	8	11	9
26	9	11	30	16	15	21	32	32	10	22	12
20	9	10	26	20	18	16	33	39	8	16	22
26	11	10	37	18	15	28	24	28	8	15	14
27	10	10	30	30	20	21	28	31	8	11	13
31	11	8	32	24	39	23	33	38	12	10	10
31	16	18	27	35	19	26	36	36	11	9	11
27	28	32	28	20	20	34	27	45	9	12	13
30	22	21	32	28	18	27	33	33	9	16	11
						IRRIGATION HEADER					

Figure 4.3). A “heat” map of substrate VMC (%) values taken 48 h after an irrigation event at different places across the growing area (capillary matting on the floor) following the interventions made at Nursery #2. N.B. plants on the double matting were in a different substrate to those in Figure 5.2C.

Conclusions

The aim of this work was to determine whether a sensor-based RDI approach to controlling plant height was feasible on capillary matting, At Nursery #1, the extent of variability in pot substrate moisture contents was generally low across the growing area when measured at different times following an irrigation event. The low variability immediately after an event (1

h) suggests that the uniformity of irrigation supply and subsequent uptake of water from the capillary matting was good, and subsequent measurements (72 and 120 h) confirmed that the rate of evapotranspiration across the growing area was also even, with the major source of variability resulting from infrastructure than the potential issues listed earlier relating to capillary matting. The data suggest that the use of capillary matting on level benches offers relatively consistent pot-to-pot substrate moisture control, and that this system would be suitable for sensor based RDI management with relatively few sensors needed.

The greater variability measured in substrate moisture contents in potted poinsettia on a floor capillary matting system could result from a range of factors. Growers recognise the effects of infrastructural influences (*e.g.,* draughts from doors etc, leaky roofs/pipework) on substrate moisture contents and try to account for these when managing irrigation systems and decision-making, but practical and financial constraints mean that inevitably, not all of these influences can be nullified. Whilst differences between bays were noted, the largest source of variability was the limited spread of irrigation water along the length of the bay. These differences suggest that it would be necessary to install a series of sensors in individual bays, and that irrigation to each of those bays would have to be applied independently. With this set-up and inherent variability, it would not be economically viable to consider using a RDI as a means of non-chemical growth control, as the extent of substrate drying could not be controlled satisfactorily. This would lead to 1) a lack of effect since the substrate would be too wet, or 2) to issues with leaf and bract damage resulting from the substrate being too dry.

These data sets highlight the inherent variability present in most growing systems and emphasize the importance of developing a robust sampling strategy to ensure that representative plants are chosen in each growing area to generate meaningful data that can be used to inform and improve decision making.

The pandemic-related delays and disruptions encountered during the project meant that our follow-on work to develop precision irrigation and deficit irrigation strategies for bedding crops grown on capillary matting systems could not be started, and so any potential impacts of these treatments on plant quality and shelf-life potential could not be addressed. Post project, opportunities to carry out the planned work on potted herb and bedding plant crops will depend on our winning research funding, and collaborative proposals will be developed for appropriate funding calls with interested project partners.

Objective 5: To establish criteria to objectively assess quality at dispatch, after distribution and during shelf-life for a range of poinsettia and pot bedding varieties

Introduction

A key aim of this project was to develop objective criteria for the assessment of plant quality at dispatch, following transport and during shelf-life tests to ensure that quality attributes are viewed consistently across the industry. At the project outset, usual practice varied from scorer to scorer, with some scoring quality from 1-5, and some from 1-10, with no clear criteria on how to allocate an overall plant quality score. In this project, criteria for the assessment of poinsettia plant quality during shelf-life tests were developed by Hilary Papworth (NIAB) and Harry Kitchener (Consultant) following discussions with the grower partners.

Materials and methods

UK and EU guidelines were used to produce standard shelf-life protocols, including relevant irrigation practices, for poinsettia varieties used in the experiments. The project Grower Advisory Panel then reviewed and refined the measurement criteria for each variety. The nomenclature and scoring system to be used to try to ascribe objective quality scores were agreed and used to assess whether RDI impacted on the deterioration of plant quality during an eight-week shelf-life test (described in Objective 2).

Following the testing of the quality criteria over the course of the shelf-life experiment, several issues and inconsistencies were identified. Further work was needed to ensure that the quality score allocated using these criteria matched our grower experts' visual perception of quality. Our aim was to develop appropriate weightings of each parameter after consultation with our grower partners to try to improve the accuracy of the allocated scores, but pandemic related delays and disruptions meant that this was not possible.

Results

The criteria developed (Table 5.1). were a good first step towards unifying the perception of plant quality across the UK poinsettia industry. However, the quality score allocated from using these criteria did not exactly match the experts' visual perception of quality; this issue can be seen by comparing the similar quality scores awarded to the CC and RDI plants on week 8 (see Figure 2.17D) with the photos taken a week later (see Figure 2.18). In the former, the overall plant quality score allocated to plants in the CC and RDI treatments at the end of the shelf-life test was similar, yet there was a large visible difference in quality one week later when the plants were viewed by the industry at the 2021 Poinsettia Day. Consequently, we sought input from our grower partners to agree and ascribe weightings to the quality criteria to ensure that the allocated score matched the visual perception of quality, but unfortunately, disruptions caused by the pandemic meant there was little useful feedback.

Discussion

The quality criteria developed and refined in his project should be used in all future work to assess the quality of poinsettia. The use of these criteria will help to quantify the relative quality of new varieties of poinsettia more objectively and consistently, and will also highlight differences in quality within the same variety grown on different nurseries, in different

Table 5.1. Initial plant quality specifications that were tested on CC- and RDI-treated "Hera" poinsettia during an 8-week shelf-life test.

Characteristic	**Observation frequency**	**Scoring type**	**Description / method**	**Description of range**
Plant height	On nursery and at final assessment	Measure	Assessment is made from pot top to tallest part of plant, but not including stray bracts	**N**/**A**
Shoot loss	Once only 24 h after sleeves removed	Count	Counts of the loss of primary shoots on removal of sleeves	**N**/**A**
Leaf drop	At each observation	Count	Observed as sleeve removed and then weekly count of drop, with a final assessment of overall loss as a proportion of the total number of leaves	**Final** score with 1 to 5 scale**: 1** = all fallen off**;** 5 = all present
Bract drop	At each observation	Count	Observed as sleeve removed and then weekly count of drop, with a final assessment of overall loss as a proportion of total number of bracts	**Final** score with 1 to 5 scale**: 1**= all fallen of**;** 5 = all present
Bract head difference in height	Once, 24 h after sleeves removed	Measure	Measure distance between the highest and lowest of the four main bract heads, using the cyathia as the point of measurement	**Pass**/**F**ail
Bract head diameter	Once, 24 h after sleeves removed	Measure	Measure width across broadest part of the bract head	**N**/**A**
Bract edge blackening	Weekly, during home-life testing	Absent/present	Observed once sleeve removed and home-life testing underway	**N**/**A**
Cyathia quality	At each observation	1 to 5	Single overall score which takes stage of development including pollen production and abscission into consideration	1=closed bud; 2=closed bud with colour showing; 3=pollen visible, stigma closed 4=no pollen, stigma open; 5=pollen visible, stigma open; 6=presence of cyathia abscission scars
Plant quality	At each observation	1 to 5	Single overall score which takes into consideration all scored aspects as well as plant habit/shape, bract position, bract colour (how it is maintained over time), cyathia colour, leaf colour.	1=unacceptable in one or more aspects 2=2nd quality, not to retail standard 3=acceptable in all aspects 4=less than excellent in one aspect 5=excellent quality in all areas

growing systems, using different cultural methods, and grown under different environmental conditions. The weighted criteria should also be used to quantify treatment differences such as those arising from work investigating different PGR formulations or application rates, or the effects of other interventions in the nursery.

Conclusions

- We investigated the use of substrate moisture sensors in several growing systems, and have discussed their respective advantages and limitations;
- The use of such sensors to measure and map variability in substrate moisture content was demonstrated in ebb-and-flow and capillary mapping irrigation systems;
- Regulated Deficit Irrigation was imposed successfully on the commercial Hera crop at Staplehurst Nursery using a combination of real-time data sets of substrate VMC, pore E.C., air temperature and VPD;
- Variability in substrate VMC before and after irrigation events, and across and between flood-and-drain benches, was monitored weekly to optimise outcomes;
- Poinsettia plant height and quality specifications at dispatch were fully met when RDI was used as a non-chemical method of growth control at Staplehurst Nurseries;
- PGR use was reduced by 85% when RDI was used to control plant stem extension;
- Shelf-life potential of RDI-treated plants was improved compared to control plants sprayed with PGRs; leaf and bract abscission were lowered by 50% and 90%, respectively, over the 8-week shelf-life test;
- Deficit irrigation applied to crops of Astro Red, Freya Red and Infinity Red at Neame Lea Nursery induced lower leaf abscission and sometimes reduced overall plant quality; later inspection showed that root systems in these plants were under-developed;
- For longer-term pot crops, the control of growth via RDI can be informed and guided by the real-time substrate moisture data;
- Criteria to assess poinsettia plant quality at dispatch and during shelf-life were developed with input from the grower partners and tested in the 2019/20 season;
- Further refinements to the quality scoring criteria should be made by industry representatives, including weightings for the main parameters to ensure that allocated quality scores better mirror visual quality.
- We established that wireless substrate moisture sensors and weighing balances can be operated in real-time in commercial glasshouses reliably, and that the data can be easily viewed remotely on various devices;
- Care is needed in interpreting data from commercial crops when calculating crop co-efficients.

Knowledge and Technology Transfer

The results of the 2019 experiments at Staplehurst and Neame Lea Nurseries were presented at the AHDB Poinsettia Open Days held at Neame Lea Nurseries on 9 November 2019 and 15 January 2020. Results from the 2019/20 shelf-life tests were also presented and demonstrated at the latter event.

An article describing the aims and objectives of the project was prepared for the AHDB News in September 2020, and a presentation on how to implement RDI on poinsettia and what to expect was made at the AHDB Webinar on Growth Control on 25 September 2020.

Videos describing the RDI work at Staplehurst Nursery, the DI work at Neame Lea Nursery, and translational work carried out by the team art Woodlark Nursery were filmed in November and December 2020 and are available on the AHDB project page.

A presentation demonstrating the range of equipment that could be used to implement and monitor RDI at various levels of expense and sophistication was made at the 2021 Poinsettia Day held at Neame Lea Nursery on 25 November 2021.

A summary of the earlier project outputs, and our recent work on deriving real-time, variety-and-developmental-stage-specific crop coefficients to facilitate the imposition of RDI to pot and pack bedding crops was recorded for the BPOA Technical Conference on 1 February 2023.

Glossary

Available water capacity - the difference in the water content at container capacity and wilting point.

Crop coefficient - A crop dependant factor used to adjust or convert a measured parameter. In this context, the value of the “crop co-efficient” can also consider pot size, efficiency of irrigation method, water absorption and retention by the growing medium as well as the type and development stage of the crop.

Deficit irrigation – the withholding, reduction, or exclusion of irrigation water from the rooting zone so that demand for water is greater than supply. This limited rootzone water availability eventually triggers changes in plant morphology, physiology and metabolism that may benefit production and or quality. Often DI is applied across the growing season and the rate and extent of substrate drying is either uncontrolled or arbitrarily chosen.

Dielectric permittivity - Sensors can be constructed to detect changes in capacitance caused by changes in the relative permittivity of soils and substrates. The volume of water in the total volume of growing medium most heavily influences the dielectric permittivity of the soil because the dielectric of water (80) is much greater than the other constituents of the soil (mineral soil: 4, organic matter: 4, air: 1). When the amount of water changes in the soil, a probe will measure a change in capacitance due to the change in dielectric permittivity that can be directly correlated with a change in water content.

Evapotranspiration - the rate at which a plant or a crop loses water under prevailing environmental conditions if water supply is non-limiting. It includes evaporation from the plants (transpiration) and from the growing medium in the pot.

Gravimetric estimate - a procedure involving the change in weight over a defined period of time of a sample of pots containing well-watered, freely transpiring plants. During the measurement period, it is important to prevent any water uptake by the pot/plant from either overhead irrigation (or rain) and sub-surface irrigation *e.g.,* flood-and drain, or capillary matting. This is best achieved by taking measurements in dry conditions and by standing pots on upturned saucers.

Photosynthetically active radiation – PAR light is the wavelengths of light within the visible range of 400 to 700 nm which drive photosynthesis.

Pot capacity - the volume or weight of water remaining in a pot of substrate after it has been fully saturated and allowed to drain freely.

Regulated Deficit Irrigation – the imposition of controlled rootzone drying events during specific developmental stages, the severity and duration of which are optimised for a particular variety or growing environment. The rationale behind this technique is to subject plant root and shoot tissues to controlled water deficits so that changes in cell turgor trigger various metabolic changes, including the production of plant hormones that induce physiological responses to the perceived stress. Often, the intensity of *in-planta* signalling is carefully regulated to optimise outcomes.

Statistical significance – helps to quantify whether a result is likely due to chance or to some factor of interest such as the effect of a specific treatment. When a treatment difference is significant, it simply means the reader can feel confident that it is a real effect, and not one resulting simply from chance. A significance level of 5% is often chosen and is usually expressed as a “p-value”. The lower the p-value (*e.g.,* 0.05), the less likely the results are due purely to chance.

Substrate volumetric moisture content - the water content of the substrate expressed as a fraction or percentage of the total volume occupied by water. Its optimum value depends on the type of substrate but for those used in the production of pot and bedding crops, it is generally between 30 and 50%.

Vapour Pressure Deficit - is the difference between the Saturated Vapor Pressure and Relative Humidity of the air. It is a measure of the amount of drying power the air has upon the plant or, in other words, how much moisture is being sucked out of the plant by the atmosphere. Higher VPDs will usually result in higher rates of transpiration and consequently higher rates of water uptake by the roots if water availability Is not limiting.

Wilting point - The water content of substrate when a plant can no longer draw water from it. At this point, the capillary forces holding the water in the growing medium just exceed the capillary pull, “suction” or substrate water tension capable of being exerted by the plant.

References

Sánchez-Blanco, M.J. et al. (2019). Deficit irrigation as a strategy to control growth in ornamental plants and enhance their ability to adapt to drought conditions. The Journal of Horticultural Science and Biotechnology Volume 94, 2019 - Issue 2.