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 EMR
Report:	Annual Report, January 2021
Previous report:	NA
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Industry Representative:	NA
Date project commenced:	1 August 2019

DISCLAIMER

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.

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Signature Date 30 January 2021

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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.

Background

In Defra-funded work carried out by NIAB EMR 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 in Poinsettia so that retailer specifications were met at market date, despite a 90% reduction in plant growth regulator (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 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 used 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 remained, 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 this project, we are working with our industry partners to develop tools, approaches and technologies to deliver DI and Regulated Deficit Irrigation (RDI) in a range of production systems currently used by small-, medium- and large-scale protected pot and bedding growers. New technologies and approaches are needed to enable DI and RDI to be scaled-up to deliver non-chemical growth control to 40,000+ poinsettia plants at Neame Lea Nurseries. Experiments are being carried out at Staplehurst Nurseries to provide unequivocal evidence of the benefits of RDI for height control, quality at dispatch and shelf-life potential of key pot and bedding species.

A key aim is 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.

A Project Exploitation sub group (PESG) has been assembled to identify opportunities for KE exchange between different sectors, and will seek to commercialise the outputs from this project and develop further R&D proposals supported by evidence gained from exploratory studies.

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 EMR 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. Sensors were wired to Advanced Dataloggers with telemetry and substrate moisture content readings from individual sensors were averaged every 15 min within treatments and uploaded into a Cloud Report and displayed on a data dashboard. A weather station also provided real-time estimates of Vapour Pressure Deficits in the glasshouse to be calculated. The NIAB EMR team used these real-time data sets 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. 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 re-irrigated. Nine fertigation events were applied to the Commercial Control during this period; the duration of irrigation events was the same in both treatments.

Measurements of plant height were made once or twice weekly on six labelled plants within the Commercial Control 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 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.

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

Criteria for the assessment of quality at dispatch were agreed with the Project consortium and were used by the Staplehurst grower team to ascribe an overall quality score to each plant. 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, width 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 significant difference was the number of primary heads in the Commercial Control plants (5.6) compared to the RDI-treated plants (4.8). The width of the largest bract star in the RDI-treated plants (26.2 cm) was greater than that in Commercial Controls (24.6 cm) but not significant. 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. 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 Nurseries. Dataloggers were placed inside the boxes to record conditions during transport and relocation.

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 assign 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.

On arrival, the Staplehurst plants were transferred to a new purpose-built shelf-life room at Neame Lea Nurseries. Plants were removed from boxes and positioned on tables in their sleeves. One week later, on 17 November 2019, the sleeves were removed, and plant pots were placed in saucers and re-arranged into in a pre-randomised order so that only the NIAB EMR team knew which plant had received which treatment. Twenty-four hours later, plant quality attributes were jointly assessed by the NIAB project team, Harry Kitchener, and the Neame Lea quality assurance team using the newly developed criteria. Plants were rewetted to 550 g once plant-and-pot weight fell to 350 g. Quality attributes were assessed weekly until 8 January 2020 when the shelf-life test was ended.

Over the 8-week shelf-life test, leaf drop was reduced by 50% in plants previously treated with RDI compared to Commercial Controls, and bract drop 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 Open Day on 15 January 2020.

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

Deficit Irrigation was applied to blocks of approximately 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 application of DI to the three varieties. Since site visits by the NIAB EMR team were limited, 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 the AHDB tracker software and shared twice weekly with the NIAB EMR team.

The DI treatment was imposed from 5 October until 4 November 2020 during which time four drying and re-wetting episodes were applied. A target lower substrate volumetric moisture content of approximately 12-13% was used. At the beginning of November, concerns were raised by the Neame Lea growing team that some plants were still wilting despite the substrate moisture content having been returned to well-watered values. On a visit to the Horseshoe Road site on 8 November 2020 by the NIAB EMR team, 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 reduced. 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 are not known.

To deliver effective knowledge exchange, knowledge transfer and training.

The results of the 2019 experiments at Staplehurst and Neame Lea Nurseries were presented at the 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. Covid-19 restrictions meant that physical meetings were no longer possible from March 2020. 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 and what to expect was made at the AHDB Webinar on Growth Control on 15 September 2020.

Financial Benefits

The costs of the sensors from Delta-T are:

- WET sensor with HH2 hand-held meter has a list price of £1303. This will measure substrate volumetric moisture content, temperature and pore E.C. It can be calibrated for different substrates to ensure accurate VMC readings. This has been routinely used across multiple projects, and many soft fruit farms use this sensor too.
- SM150-sensor with hand-held reader is £393. This will measure substrate volumetric moisture content only. This is a read only meter – i.e. no download or record function or capacity to install substrate specific calibrations.

Cost savings in the purchase and application of PGRs are anticipated if the project is successful and a commercial RDI scheduling service is developed for pot and bedding plant growers.

A partial cost/benefit analysis of using RDI as a non-chemical means of growth control will be prepared by the Project Exploitation Sub Group (PESG) and presented in the Final Project Report.

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:

- 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.

SCIENCE SECTION

Introduction

One of the key priorities of the AHDB Horticultural strategy is 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 poinsettias, 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 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 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 bract and leaf drop during shelf-life tests were reduced by 90% and 50% 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 (SVMC) in these pots were monitored every 15 minutes 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 SVMC 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 spec. 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 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 builds on the success of the commercial deployment of deficit irrigation (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 have continued to develop the technologies and approaches needed to enable the DI work to be scaled-up to deliver non-chemical growth control to 40,000+ poinsettia plants at Neame Lea. We have carried out statistically robust experiments at Staplehurst Nurseries to provide unequivocal evidence of the benefits of precision Irrigation (PI) and DI for height control, quality at dispatch and shelf-life potential of key pot and bedding species. We continue to work with our industry partners to develop tools, approaches and technologies to deliver PI and DI in a range of production systems currently used by small-, medium- and large-scale protected pot and bedding growers.

A key objective is 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. A Project Exploitation Sub Group will identify opportunities for KE exchange between different sectors, and will seek to commercialise the outputs from this project, and develop further R&D proposals supported by evidence gained from scoping studies.

Materials and methods

Experiment 1 – Staplehurst Nurseries

<u>Plants and commercial growing conditions</u>

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 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 1). Irrigation / fertigation to the CC crop was scheduled by the Staplehurst team who decided on the frequency of irrigation event; the duration of each irrigation event

Figure 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.

was set at 24 minutes which ensured an even distribution of water across each flood-and-drain benches 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 EMR 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 Delta T sensors (SM150T) 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 an RDI irrigation block (Figure 1). The sensors measured the dielectric permittivity of the substrate and were inserted carefully into the substrate of nine representative pots (Figure 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 EMR project team; real-time data was also displayed on a "Dashboard" that was available to the NIAB EMR team but not to the Staplehurst growing team.

Figure 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.

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 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 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 ebb-and-flow irrigation system on 11 September 2019. Subsequent changes in plant-and-pot weights and substrate VMC values were made frequently by NIAB EMR 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 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 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 EMR project team before 08:00 and a recommendation on whether or not to irrigate was sent to the grower team via a WhatsApp group that also included the NIAB EMR project team. Follow-up phone calls were made if further discussion was needed, or 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 EMR team.

In early September 2019, moisture sensors were placed into nine pots sited across a bench within an irrigation block in both the CC and RDI treatments. Sensors were wired to the GP2 Dataloggers with telemetry, and substrate VMC readings from individual sensors were averaged every 15 min within treatments and uploaded into a Cloud Report, and were displayed on the dashboard. A weather station also provided real-time readings of photosynthetically active radiation (PAR), and air temperature and RH measurements enabled estimates of Vapour Pressure Deficits (VPD) in the glasshouse to be calculated (Figure 5). The NIAB EMR team used these real-time data sets 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.

Figure 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 remotely monitored 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 irrigated. 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 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 Staole 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 were agreed with the Project consortium and were used by the Staplehurst grower team to ascribe an overall quality score to each plant. 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, width 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.

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.

Experiment 2 – Neame Lea Nursery

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”, “Infinity Red”, and “Freya Red” were potted in industry standard poinsettia mix - 15 mm peat plus 20% by volume medium grade perlite (Figure 6). 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 6. 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.

Imposition of Deficit Irrigation

A technology package consisting of nine Delta-T 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 7) 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

Figure 7. 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.

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 or not 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.

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 RDI pre-conditioning treatment was applied from 12 – 21 September 2019 during which time the substrate VMC was reduced to 18% before re-wetting. RDI was then applied from 22 September to 9 November 2019.

The RDI 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 RDI strategy was agreed with the Production Manager to try to bring the three varieties plants back within spec. 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 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.

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

Experiment 1 – Staplehurst

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 8 (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 8A). The aim in the RDI treatment was to avoid large fluctuations in substrate VMC as previous work has shown that

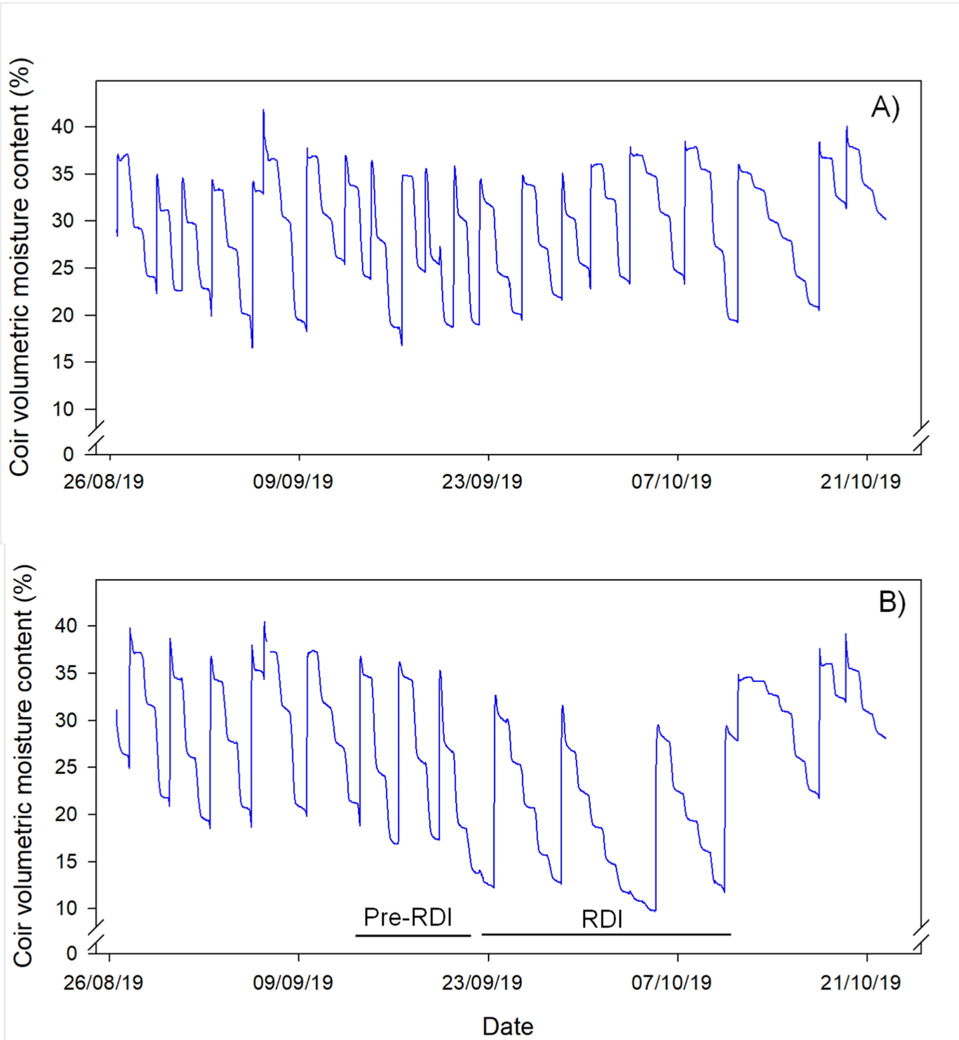

Figure 8. Changes in substrate VMC in A) Commercial Control and B) RDI pots during the growing season. Values are the mean of readings from nine sensors in each treatment. In B), the duration of the RDI pre-conditioning phase in which substrate VMC was reduced gradually, and the RDI phases are shown.

these can reduce plant quality, uniformity, and robustness. Seventeen 24-min irrigation events were applied from 11 September to 31 October 2018 (Figure 8B).

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 9A&B). Pore E.C. values were variable over this time (Figure 9C) and were likely influenced by the increasingly dry substrate, and so values should be viewed with caution and not over-interpreted. Initially, rates of evapo-transpiration 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 9D). At this point, on 15 September 2019, visible wilting was apparent at 10:30 (Figure 10A). The six plants were then re-watered to return substrate VMC values to pre-stress levels. Within 24 h of re-watering previously wilted plants, all plants regained turgor and were indistinguishable from their well-watered counterparts (Figure 10B). 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.

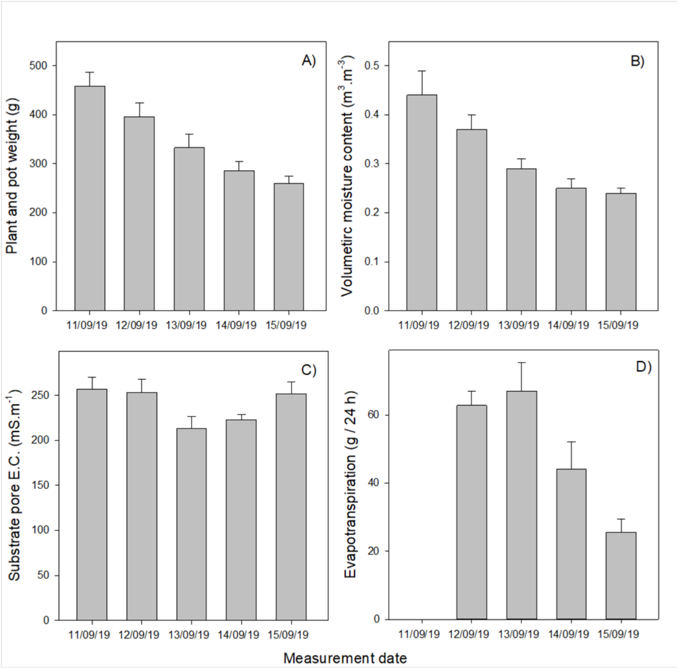

Figure 9. Changes in A) plant-and-pot weights, B) substrate VMC values, C) substrate E.C. and D) evapotranspiration rate during a period in which irrigation was withheld. Values are means of six replicates with associated standard errors.

Figure 10. 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 11). 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 schedecision irrigation and RDI using predicted glasshouse VPD values.

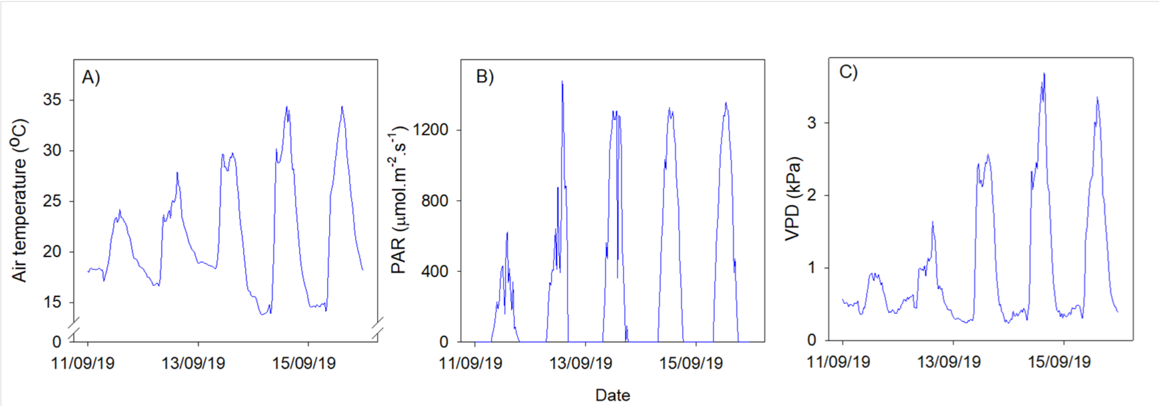

Figure 11. Diurnal changes in A) air temperatures, B) PAR and C) VPD during the 5-day drying cycle imposed to establish the wilting point in Hera.

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 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 12). During the pre-conditioning phase, the plant-and-pot weights on bench #2 in RDI irrigation block 5 varied from 440 – 500 g (Figure

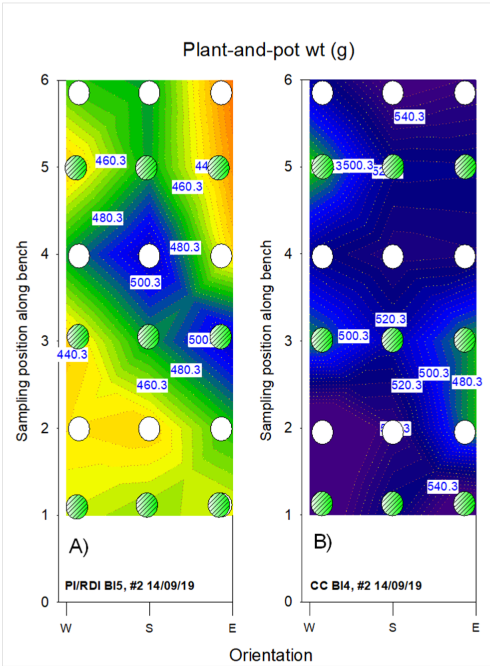

Figure 12. Contour maps of plant-and-pot weights across the bench in A) RDI and B) the CC treatments. Circles represent measurement points and green circles show the position of pots in which SM150T sensors were installed. Blue colours indicate wetter substrate and green-yellow colours drying substrate.

12A), while those on bench 2 in CC irrigation block 4 ranged from 480 – 550 g (Figure 12B). The wetter area in the middle of the bench (Figure 12A) 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 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

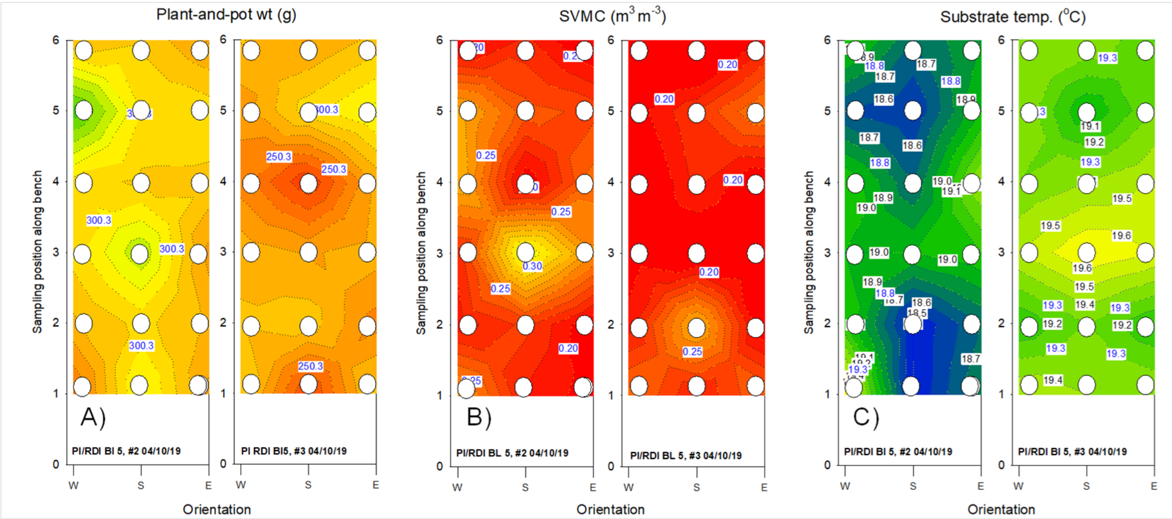

Figure 13. Contour maps of A) plant-and-pot weights, B) substrate VMC and C) substrate temperature across two benches in RDI irrigation block #5. Circles represent measurement points. In A) orange indicates lighter pots, in B) red indicates drier substrate, and in C, yellow indicates warmer substrates.

that variability across and between benches was low at this critical time (Figure 13).

<u>Changes in the rate of change of substrate drying under RDI</u>

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 14). On consecutive days with a similar VPD, a change in this slope was interpreted

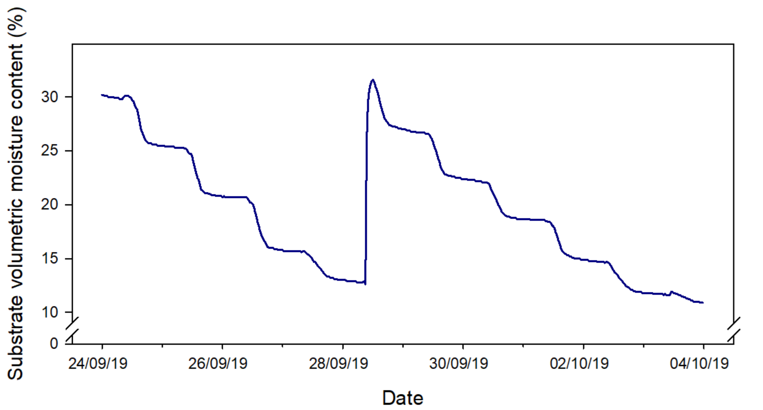

Figure 14. Differences in plant water uptake during the day and night cause characteristic "stepping" In the substrate VMC traces. The slope of these steps can be used to identify when a rootzone moisture deficit stress triggers partial stomatal closure, indicating that the plants are perceiving the stress.

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

PGR control of plant height in Commercial Control plants

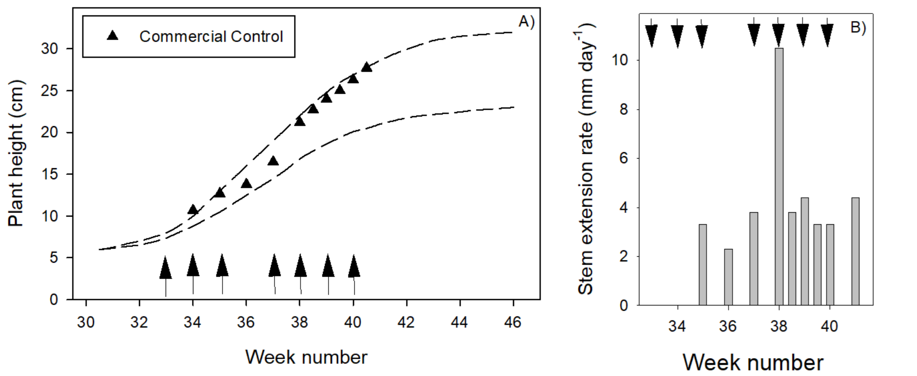

Figure 15. A) Plant height increases over the season and B) the rate of stem extension in Commercial Control plants. Values are means of six replicate plants. Arrows indicate the timing of PGR applications. In A) plant heights are plotted relative to the upper and lower height specifications for the crop.

The PGR applications were applied to the Commercial Control 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 27 and 38 (Figure 14 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.

Effects of RDI on Hera stem extension

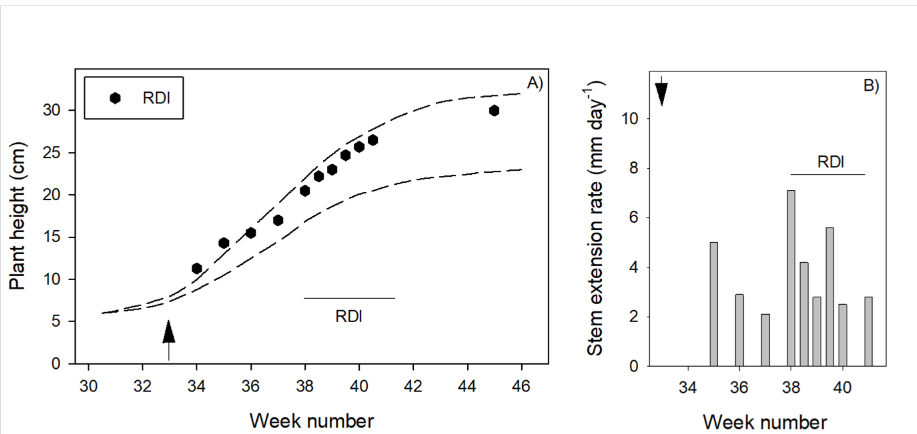

Figure 16. A) Plant height increases over the season and B) the rate of stem extension in RDI-treated plants. Values are means of six replicate plants. Arrows indicate the timing of PGR applications. In A) plant heights are plotted relative to the upper and lower height specifications for the crop.

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 latest plant height data provided by the Staplehurst team (Figure 16A) 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 16B). 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.

<u>Visual differences in the CC and the RDI crops</u>

Visible differences in leaf colour were noted towards the end of the RDI treatment; leaves on RDI-treated plants were a paler green (Figure 17) 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 since only four fertigation events were applied during the RDI period, compared to nine fertigation events received by the Commercial Control 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 17. 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 17). This was presumably a consequence of the limited use of PGRs which are known to accelerate bract formation and cyathia development.

<u>Plant quality at dispatch</u>

The quality attributes to be assessed at dispatch were agreed by the consortium and are listed in Table 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 EMR 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 just 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 plants in this random sample. There were no visible differences between CC and

Table 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 18. A) RDI-treated and B) Commercial Control plants on the day before dispatch. Photos taken on 7 November 2019.

RDI-treated plants (Figure 18).

<u>Shelf-life test</u>

The quality criteria developed by the consortium to assess quality more objectively during shelf-life are given in Appendix 2. The rate of deterioration in plant quality of Commercial Control 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 Commercial Controls, and bract abscission was reduced by 90% in RDI-treated plants; both differences were statistically significant (p<0.05) by Week 4 (Figure 19

A&B). Cyathia development was delayed by RDI until week 4 after which values were the same in each treatment (Figure 19C). Overall plant quality was higher in RDI-treated plants on five of the seven measurement dates (Figure 19D), 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 20 A&B).

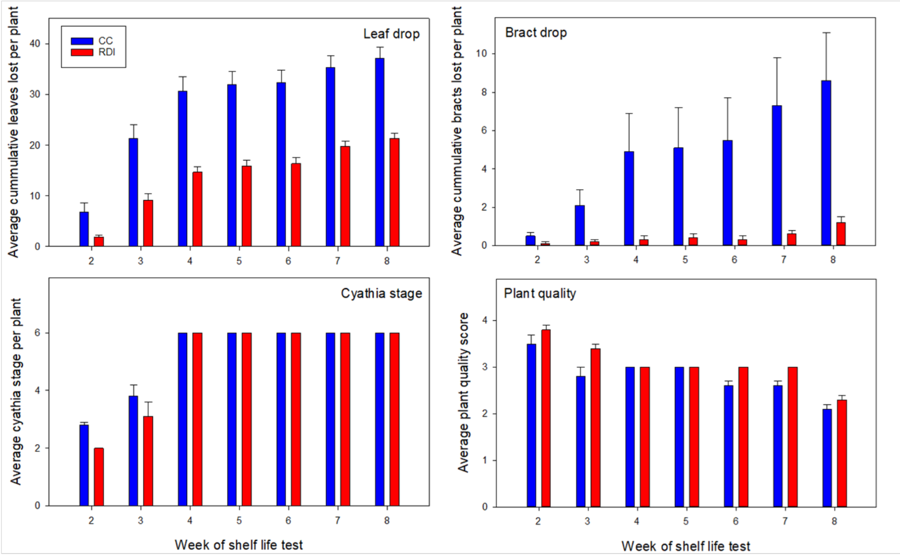

Figure 19. Poinsettia quality parameters measured during the shelf-life test at Neame Lea Nursery on Commercial Control plants and those previously treated with RDI. A) average cumulative leaf fall per plant, B) bract fall, C) cyathia stage and D) subjective quality score. Results are means of 12 replicate plants with associated standard errors. Treatment effects on leaf and bract drop were statistically significant from Week 4 (p<0.05).

Figure 20. 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.

Experiment 2 – Neame Lea Nursery

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 specs. A more aggressive DI strategy was needed and so the number of drying and re-wetting cycles was increased from the usual three to four to five in the case of Astro Red and Freya Red (Figure 21A&B), and 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 22).

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 23 A&C). However, the rate of stem extension in Freya Red was not initially slowed by DI (Figure 23B), and so a more severe stress was imposed to try to slow stem extension. Whilst these aggressive DI strategies generally brought

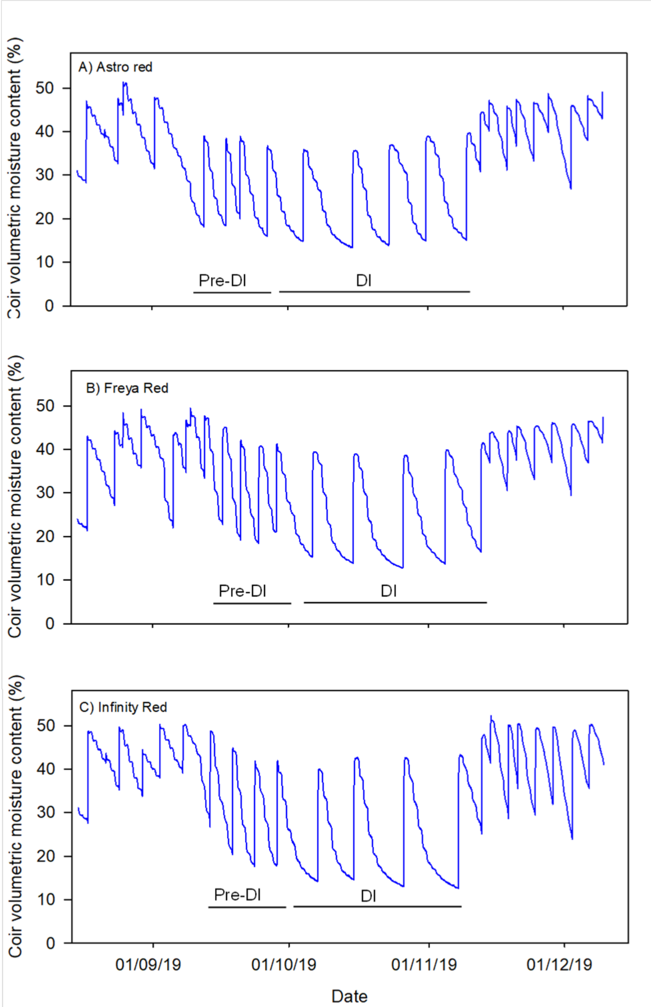

Figure 21. Changes in substrate VMC in A) Astro Red, B) Freya Red and C) Infinity Red during the growing season. Values are the mean of readings from nine sensors in each treatment. The duration of the DI pre-conditioning phase in which substrate VMC was reduced gradually, and the DI phases are shown.

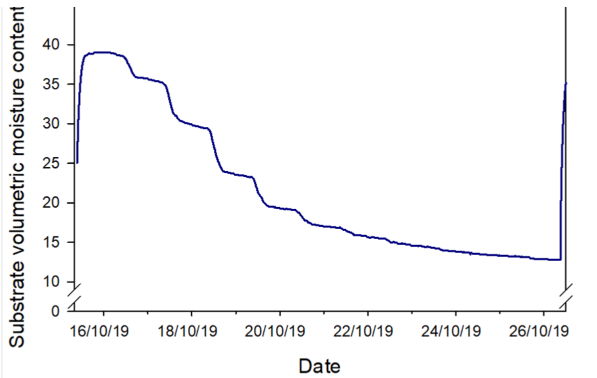

Figure 22. Prolonged exposure to dry substrate to try to limit stem extension in Freya Red following the mid-season change in height specification.

plants heights back into, or near to, the new lower height spec., plant quality was impacted

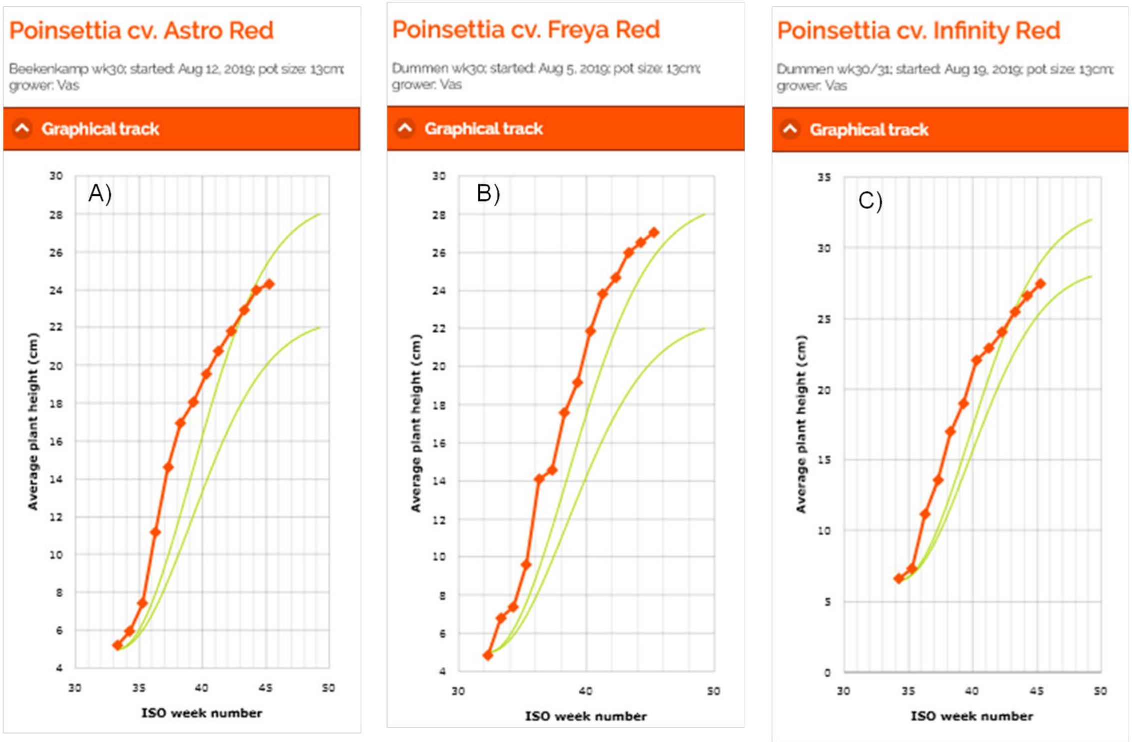

Figure 23. Effects of DI on plant height in A) Astro Red, B) Freya Red and C) Infinity Red at Neame Lea Nursery.

(see below).

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 24A). 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 24B), even though VPD values were low during the

Figure 24. 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.

recovery phase. On examination, the root systems were poorly developed in many of these three varieties (Figure 24C).

Discussion

One of the key priorities of the AHDB Horticultural strategy is to generate innovative R&D and KE to improve the productivity, resilience and sustainability of horticultural production systems. In addition to the imminent withdrawal of PGRs, the industry must be ready to address wider challenges including legislation to reduce emissions and safeguard the environment; the need to grow more with less in a changing climate, reducing waste, the effective use of digital technologies and the creation of highly skilled technical posts, and a greater provision of locally-sourced produce to help to reduce transport costs and GHG emissions. There remains fierce competition from the Netherlands, who account for 74% of all UK ornamental imports, and so new innovative, data-driven, resource efficient technologies are needed to support climate-smart and resilient bedding and pot plant production in the UK.

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 EMR to enable frequent site visits to make measurements. Previous experience of using RDI and a willingness to accommodate the requests of the NIAB EMR science team were also important considerations. For these and other reasons, the owner of Staplehurst Nurseries Ltd, Marcel Franke, was asked to host an experiment that focussed on generating scientifically and statistically robust data sets to provide unequivocal evidence on the potential to use RDI as a non-chemical method of growth control.

In 2019, Neame Lea also continued their strategy of growing 40,000+ poinsettia without reliance on PGRs, which they have been doing successfully since 2016. The focus on the work at Neame Lea in 2019 was to two-fold: 1) test the potential to deficit irrigation to limit stem extension in three varieties, and 2) devise approaches that could be used to scale-up the RDI approach across the nursery, without reliance on tens of precision irrigation technology units.

The two experiments at Staplehurst and at Neame Lea therefore had different objectives and were carried out at different scales. The experiment at Staplehurst was closely monitored by the NIAB EMR 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. This level of input was not possible or appropriate in the Neame Lea experiment and so a more straightforward Deficit Irrigation treatment was imposed that relied on the interpretation of remote data sets by the NIAB EMR team, coupled with observational input from the Neame Lea growing team.

For RDI to be implemented effectively and consistently, it is necessary to identify how factors that will 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. 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 13B 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. Work in Project Year 2 will focus on measuring the variability in the aerial environment across the growing area at Staplehurst to better understand how this can be managed to improve uniformity of plant growth and quality. Similar measurements were made on the smaller benches at Neame Lea and showed that irrigation system performance was sufficiently uniform to enable DI to be applied.

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 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 RDI 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 spec., but the poor rooting development was more widespread and was apparent in other varieties outside of the DI trial. There were already quality issues reported by the growing team from the application of SB Plant Invigorator B spray on 16 September 2019 – this led to leaf scorch and abscission in Freya Red (Figure 24A), 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 in order 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, 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.

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 yet known but could include differential sensitivities to the plant hormones ethylene, abscisic acid and auxins 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 side effect of applying RDI during the exponential growth phase to limit stem extension. Again, further research is needed to identify which varieties would respond best.

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. Without these, it is impossible to maximise the outputs and knowledge generated from grower trials and more scientific experiments. The criteria developed here are a good first step towards unifying the perception of plant quality across the UK poinsettia industry. However, further work is needed to ensure that the quality score allocated from using these criteria matches 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 (Figure 19D) with the photos taken a day later (Figure 20). In Project Year 2, we will seek input from our grower partners to agree and ascribe weightings to the quality criteria to try to improve the accuracy of the allocated scores.

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 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

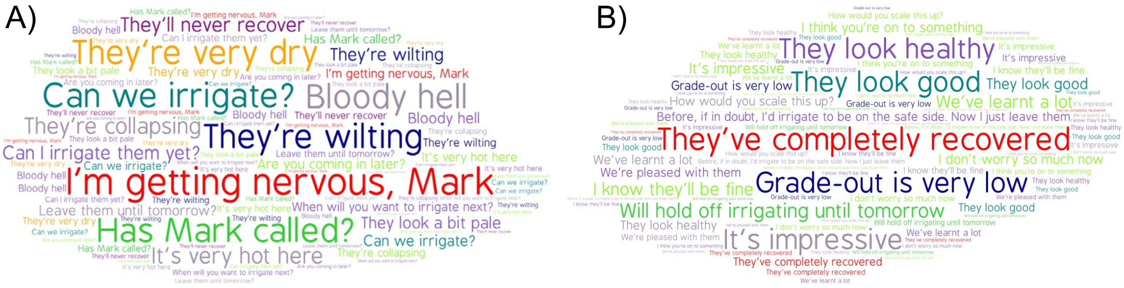

Figure 25. Comments from the Staplehurst growing team captured A) during the RDI drying episodes and B) following plant recovery following re-wetting events and the end of the RDI treatment.

messages and conversations over the phone and in person (Figure 25A). 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 EMR project team. 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 25B). The growing team at Staplehurst are now far more confident and willing to hold off on irrigating for an extra day and are keen to explore how the benefits of RDI can be extended across the nursery and to other crops. This work will be carried out in Project Year 2.

Despite the disappointing results from the 2019 work at Neame Lea, the team are committed to continuing with their nursery-wide “dry growing” regime, but they recognise that more experience of the different varietal responses is needed in combination with detailed data sets to inform decision-making during the imposition of DI. In Project Year 2, approaches to scaling-up the DI work across the nursery along with measures to mitigate the risks will be developed and tested.

Progress against milestones for each of the eight objectives in 2019/20 is shown in Appendix II and reasons and explanations for delays are provided.

Conclusions

- Regulated Deficit Irrigation (RDI) was imposed successfully on the commercial Hera crop at Staplehurst Nursery using a combination of real-time data sets of substrate moisture contents, pore EC, air temperature and VPD;
- Variability in substrate moisture contents 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;
- 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 were made by including weightings for the main parameters to ensure that allocated quality scores better mirrored visual quality.

Knowledge and Technology Transfer

The results of the 2019 experiments at Staplehurst and Neame Lea Nurseries were presented at the 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 for the AHDB Webinar on Growth Control on 25 September 2020.

Project consortium meetings were held at Neame Lea Nurseries on 2 August 2019 and at Staplehurst Nursery on 13 October 2019. Covid-19 restrictions meant that physical meetings were no longer possible from March 2020. Project Technical and Review meetings were held remotely on 15 April and on 5 November 2020.

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 take into account 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 in order 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.

Appendix I – Plant quality specifications for use during shelf-life tests

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	not on nursery but then 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 with 1= all fallen off, to 5= all present
Bract drop	not on nursery but then 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 with 1= all fallen off, to 5 = all present
Bract head difference in height	once only 24 hrs after sleeves removed	measure	measure the distance between the highest and lowest of the 4 main bract heads, using the cyathia as the point of measurement	pass/fail
Bract head diameter	once only 24 hrs 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

Appendix II (please remove prior to publication)

The information in this Appendix s intended for AHDB use only in order to tracj project progress and should be removed prior to the publication of this report.

Milestone schedule – linked to core objectives

No.	Milestones	Organisation Responsible	End Date	Comments
1	**Project Management and Reporting**	All	31/10/21	On-going
1.1	Kick-off meeting hosted at Neame Lea	Neame Lea	31/07/19	Completed
1.2	SLP Plan and Risk Register developed	NIAB EMR	30/09/19	On-going
1.3	Annual and Final Reports submitted	NIAB EMR	30/09/21	On-going
2	**Scaling-up PI and DI in commercial production**			
2.1	PI and DI used on 40,000+ poinsettia	Neame Lea	14/12/19	Completed
2.2	Ancillary wireless sensor system developed	30MHz	31/12/19	Delayed
2.3	Nutrient inputs needed during DI determined	Bulrush	31/12/19	Delayed
3	**Quantify the effects of DI on plant quality**			
3.1	Sensors and technology packages installed	NIAB EMR	30/09/19	Completed
3.2	Prototype wireless weighing platforms tested	30 MHz	31/10/19	Delayed
3.3	Effects of PI and DI on plant quality determined	NIAB	30/11/19	Completed
4	**PI and DI developed for pot bedding species**			
4.1	Target VSMC set points identified for each species	NIAB EMR	31/03/21	Completed for Poinsettia
4.2	Potential of PI/DI to improve quality determined	NIAB	30/09/21	Completed for Poinsettia
4.3	DI grower guidelines produced for pot bedding	NIAB EMR	30/09/21	
5	**PI and DI tested in different growing systems**			
5.1	Factors that complicate irrigation scheduling	Bulrush	30/11/19	Completed for Poinsettia
5.2	Data reviewed and technologies identified	Bulrush	28/02/20	Completed
5.3	PI/DI imposed on bedding crops on capillary mats	Bulrush	30/09/21	
6	**Objective criteria to assess plant quality**			
6.1	Measurement criteria for each variety agreed	HK Consultancy	30//11/20	Completed for Poinsettia
6.2	Conditions during distribution measured	NIAB EMR	30/09/20	Completed for Poinsettia
6.3	Effects of PI and DI on plant quality determined	NIAB	30/09/21	Completed for Poinsettia
7	**KE, KT and training**			
7.1	KE/KT events at Grower Partners' sites held	NIAB EMR	31/05/21	On-going
7.2	Feature articles submitted to AHDB Grower	NIAB EMR	30/06/21	On-going
7.3	Grower case studies completed	NIAB EMR	31/03/21	On-going
8	**Exploitation of project outputs**			
8.1	Project Exploitation Sub Group meetings held	Woodlark	31/01/20	Delayed
8.2	Commercial PI/DI service offer developed	Woodlark	30/06/20	On-going
8.3	Recommendations to inform further calls	SA Ltd	30/09/21	

Explanation of delays

2.2. A wireless sensor system is available from project partner 30MHz and has been tested in a block of commercial poinsettia at Volmary Ltd. The system uses moisture sensors with lower accuracy and precision that the Delta-t Devices SM150T sensors used in the work at Staplehurst and Neame Lea, and further work is needed to establish whether RDI could be imposed with sufficient precision using these alternative and less expensive sensors. A wireless sensor system is expected to be released by Delta-T Devices in the next year or so.

2.3. The need for a modified fertigation programme for poinsettia subjected to RDI was anticipated following the observation hat leaf colour was altered, presumably due to the reduction in the frequency of fertigation events that accompanies RDI. However, results over two seasons at Staplehurst Nursery showed that foliar nutrient concentrations were returned to control values between the end of the RDI treatment and dispatch, and nutrient analyses did not detect significant differences in foliar macro- and micro-elements in samples collected from Commercial Control plants and those recently exposed to RDI.

3.2. The significant delay in the provision of a wireless weighing balance by 30 MHz is impacting on the second phase of the work programme in which the suitability of RDI for use with pot and pack bedding will be tested. Additional work was carried out on a poinsettia crop at Staplehurst Nursery in Autumn 2020 in which the NIAB EMR Team intended to stress test and ground-truth the wireless balance but further delays meant that this wasn't possible. The current plan is to carry out this work at NIAB EMR in early 2021 before deployment and further development at Staplehurst in the spring of 2021.

8.1. Limited time availability of the grower partners coupled with Covid-19 related restrictions has meant that the PESG has not yet met to discuss project exploitation activities and opportunities. Efforts to organise this meeting will resume in 2021.

More generally, the series of Covid-19-related lockdowns and restrictions in 2020 and 2021 have meant that we have been unable to begin the work programme on pot and pack bedding as originally planned. The project work programme and Gantt chart is currently being updated and suggested workarounds and timescales will be discussed with AHDB MO.

