Project title:	Developing optimum irrigation guidelines for reduced peat, peat-free and industry standard substrates
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Project leader:	Dr Mark A. Else, East Malling Research
Report:	Annual report, March 2011b
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Location of project:	East Malling Research
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Date project commenced:	1 April 2010
Date project completed (or expected completion date):	31 March 2013

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.

Fiona Wilson
Project Manager
East Malling Research

Signature .... Date ....

Dr Mark A. Else
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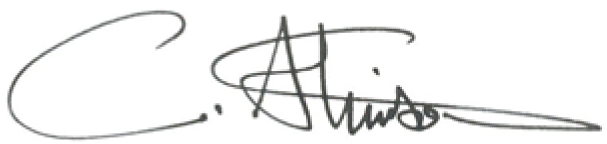
Report authorised by:

Dr Christopher J. Atkinson
Programme Leader
East Malling Research



October 2012

Signature .... Date ....

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GROWER SUMMARY

Headline

- The optimum range of substrate water contents for reduced peat, peat-free and industry standard media have been identified
- Irrigation set points for the three substrates that optimise plant quality but minimise losses of water and fertiliser were determined

Background and expected deliverables

The HNS sector is the largest user of peat in the UK horticultural industry. Around 450,000 m^3 of growing medium, of which about 80% is peat, is used annually for hardy nursery stock production in the UK. Although some customers request peat-free production (*e.g*. The National Trust), the majority do not and so at the moment, there is little commercial pressure to reduce peat use. However, following the publication of Defra's consultation document in December 2010 ('Consultation on reducing the horticultural use of peat in England 2010'), many growers are becoming increasingly concerned about the proposed phasing out of peat in the horticultural industry. For the Government and the public sector, the target is to be peat free by 2015; and for the professional horticulture and landscaping sectors to be peat free by 2030 at the latest.

Most growers acknowledge that irrigation and nutrient regimes will need to be modified when using reduced peat and peat-free substrates. The relatively poor water-holding capacity of most peat-free alternatives will necessitate more frequent irrigation events but over-watering must be avoided to minimise run-through of water and dissolved fertilisers and limit environmental pollution. To help facilitate the development of 'best' or 'better' irrigation practice during the proposed transition to peat-free production, new scientifically-derived irrigation set points are needed that optimise substrate moisture content for the reduced peat and peat-free media likely to be used by HNS growers in the future.

In this project, the 'optimum' substrate moisture content is defined as one that supports good, healthy plant growth while avoiding over-wet conditions so that leaching of irrigation water and fertilisers is minimised or eliminated. Irrigation set points will be identified for each substrate and used to develop new guidelines to help growers overcome problems associated with over-watering reduced peat and peat-free alternatives.

The overall aim of the project is to develop and implement improved irrigation scheduling guidelines for reduced peat, peat-free and industry standard media that help growers comply with legislation, optimise plant quality, reduce costs and gain confidence in growing HNS in peat alternatives.

Summary of the project and main conclusions

Experimental plant species and commercially available reduced peat, peat-free and industry standard substrates were selected after consultation with members of the project steering group. The following widely-produced crops were chosen as they are moderately resilient to substrate drying and so were considered a good choice of 'indicator' species:

- *Sidalcea oregana* 'Party Girl'
- *Ribes sanguineum* 'Koja'
- *Escallonia rubra* 'Crimson Spire'

The following substrates were chosen (for use in years 1 and 2) since they are considered to be good quality brands that are (or are becoming) widely used by UK growers:

- **Industry standard:** substrate based on 25% bark, 75% peat supplied by Sinclair
- **Reduced peat:** substrate based on 25% wood fibre, 25% bark, 50% peat supplied by Bulrush
- **Peat free:** substrate based on peat-free materials (composted green waste and bark) supplied by Vital Earth

Specification details were obtained for each substrate; additionally each was analysed for air filled porosity, particle size distribution, pH, density, dry matter, dry density, Ca, Cl, Mg, P, K, Na, N, EC and trace elements. The results of these analyses are given in Appendix I (Tables A1, A2).

Bare-rooted *Sidalcea* and 9 cm liners of *Ribes* and *Escallonia* were potted in to 2 L pots containing one of the three substrates. Controlled release fertiliser (Osmocote Pro 12-14 month, 18+9+10 +2 MgO + trace elements) was incorporated at 3 kg per 1000 L for *Sidalcea* and 5 kg per 1000 L for *Ribes* and *Escallonia*. All plants were grown on in a glasshouse maintained at 15 / 10 ºC (day / night) with supplementary lighting supplied from sodium lamps during a 12 h photoperiod. Plants were hand-watered during establishment. The frequency and duration of irrigation events required to replace water lost by transpiration was then calculated daily. Irrigation was supplied to each pot *via* a dripper stake and bootlace connected to a pressure compensated 2 L h^{-1} emitter (Figure GS1).

Figure GS1. Irrigation was scheduled to *Sidalccea* to match demand with supply. Photo taken on 23 March 2011

To establish irrigation set points a controlled environment is required, therefore the plants were maintained under glass for the duration of the experiment.

To identify the optimum range of substrate moisture contents, the approach adopted was to first determine volumetric substrate moisture content (VSMC) at 'pot capacity' then impose gradual substrate drying on half of the plants and monitor physiological responses such as stomatal conductance, transpiration rate and leaf extension growth (Figure GS2). *Sidalcea* were used for the first experiment once the root system was fully developed and plants were transpiring freely.

The VSMC at which statistically significant differences in physiological responses between the well-watered (WW) and water-limited (WL) treatments were first detected were identified. The VSMC at which wilting was first observed and at which permanent wilting occurred were also determined for each substrate.

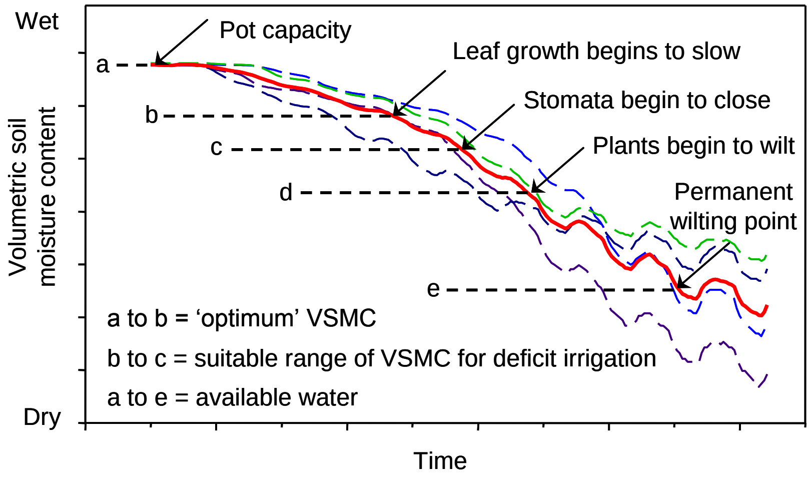

Figure GS2. Theoretical framework used to identify optimum substrate moisture contents of the different substrates. The solid line represents mean VSMC. Plant physiological responses to drying soil do not always occur in this order

Sidalcea

Physiological responses to substrate drying were first detected in *Sidalcea* plants growing in the peat-free and 50% peat mixes (Figure GS3). Although leaf extension rate is the first detectable response to substrate drying in many plant species, in *Sidalcea* trans-pirational water loss and stomatal conductance were the most sensitive and reliable indicators of drying substrate (Figure GS3).

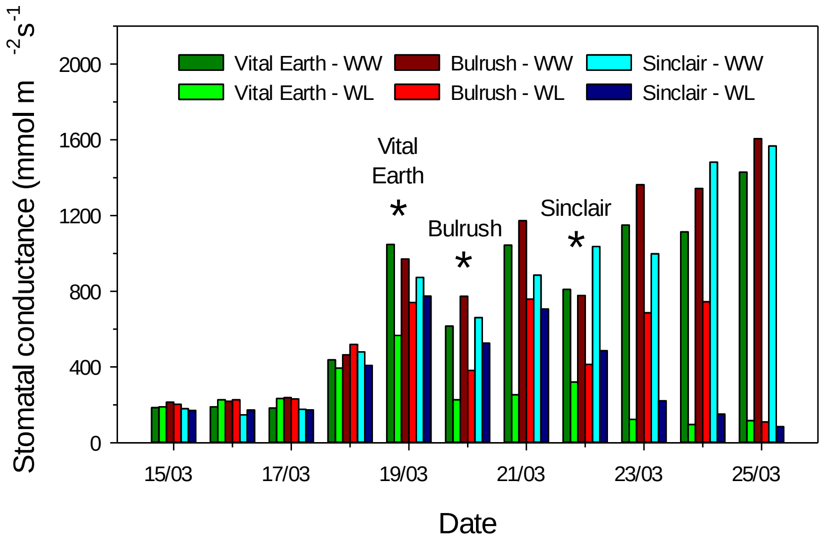

Figure GS3. Statistically significant differences in stomatal conductances between well-watered (WW) and water-limited (WL) treatments were first detected on March 19, 20 and 22 for *Sidalcea* plants grown in Vital Earth, Bulrush and Sinclair substrates, respectively

The onset of wilting was delayed by one day in plants grown in the industry-standard substrate; first signs of wilting were noted on some plants in the reduced-peat and peat-free substrates on 19 March 2011. By 21 March 2011, the extent of wilting was similar in all water-limited treatments and the degree of wilting continued to develop at similar rates thereafter (Figure GS4). Average plant heights on 29 March 2011 were 29, 30 and 27 cm in well-watered Vital Earth, Bulrush and Sinclair substrates, respectively. Average heights were reduced by 38, 40 and 4% in water-limited Vital Earth, Bulrush and Sinclair substrates, compared to well-watered values. No differences in overall plant quality were noted and all well-watered plants were classed as ‘marketable’ by the project steering group.

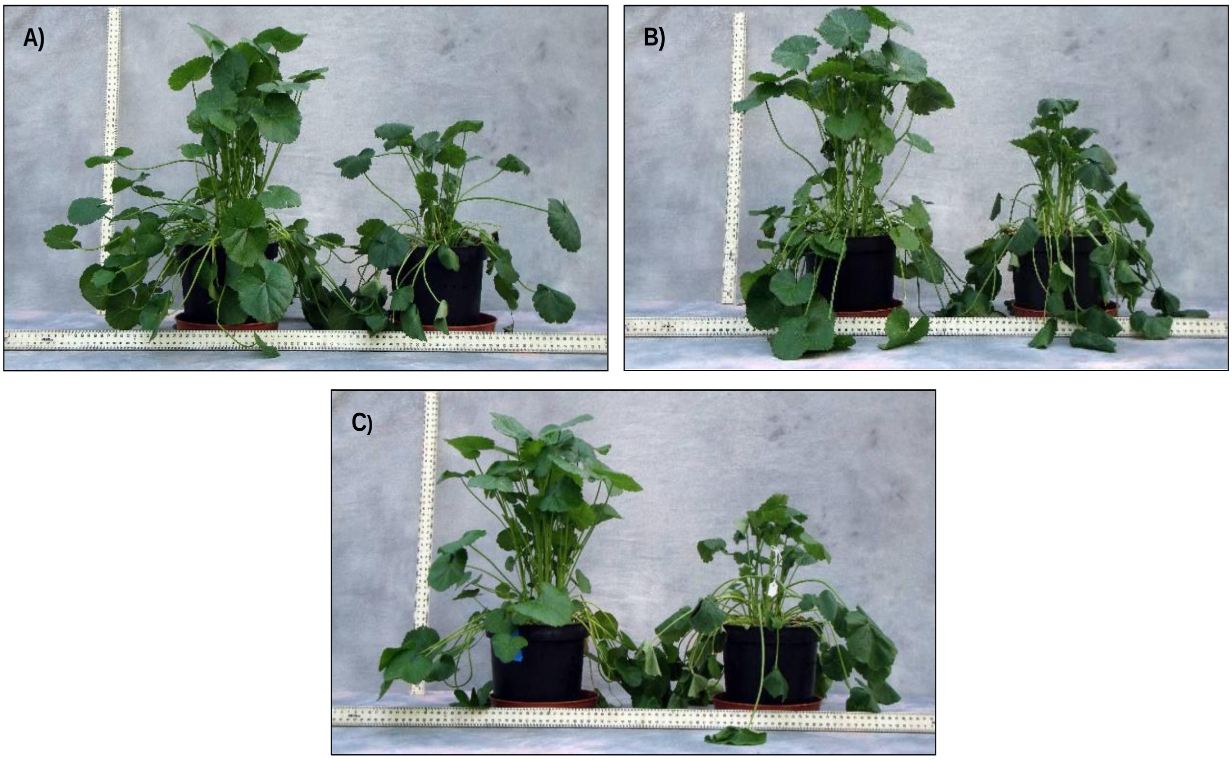

Figure GS4. Well-watered and water limited *Sidalcea* grown in A) Vital Earth, B) Bulrush and C) Sinclair substrates. Photos were taken on 25 March 2011

Table GS1. *Sidalcea* plant-and-pot weights and VSMC for each of the three substrates when significant differences in physiological responses were first detected in water-limited plants compared to well-watered plants. Results are means of seven replicate plants with associated standard errors of the mean values

Physiological parameter	Pot weights and VSMC when physiological response first detected					
	Vital Earth		Bulrush		Sinclair	
	Weight (g)	VSMC (m^3 m^{-3})	Weight (g)	VSMC (m^3 m^{-3})	Weight (g)	VSMC (m^3 m^{-3})
Stomatal conductance	1079 ± 54	0.251 ± 0.03	986 ± 72	0.247 ± 0.03	920 ± 26	0.187 ± 0.01
Whole-plant transpiration	1079 ± 54	0.251 ± 0.03	1092 ± 65	0.247 ± 0.03	987 ± 40	0.217 ± 0.01
Evapotranspiration per degree hour	1079 ± 54	0.251 ± 0.03	1092 ± 65	0.247 ± 0.03	987 ± 40	0.217 ± 0.01
Petiole extension	992 ± 51	0.214 ± 0.03	702 ± 23	0.155 ± 0.02	1036 ± 41	0.231 ± 0.02

The optimum range of substrate moisture content lies between the VSMCs at the point when physiological responses are triggered (Table GS1) and pot capacity. However, a ''low risk' strategy was developed to accommodate the inevitable logistical constraints to irrigation scheduling that occur during commercial production. Thus, the VSMC recorded 24 h before the initiation of the most sensitive response was used as the lower irrigation set point (Table GS2). Corresponding plant-and-pot weights are also presented.

Table GS2. The range of optimum values for plant-and-pot weights and VSMCs for *Sidalcea* grown in each of the three substrates. Results are means of seven replicate plants growing in 2 L pots

Substrate	Optimum plant-and-pot weights and VSMCs for each substrate			
	Pot weight (g)		VSMC (m^3 m^{-3})	
	Pot capacity	Lower	Pot capacity	Lower
Sinclair	1470	1036	0.55	0.23
Bulrush	1310	1130	0.46	0.34
Vital Earth	1370	1130	0.46	0.29

Ribes

Physiological responses to substrate drying were first detected in *Ribes* plants growing in the peat-free mix, indicated by a significant decrease in transpirational water loss four days after withholding water (Figure GS5).

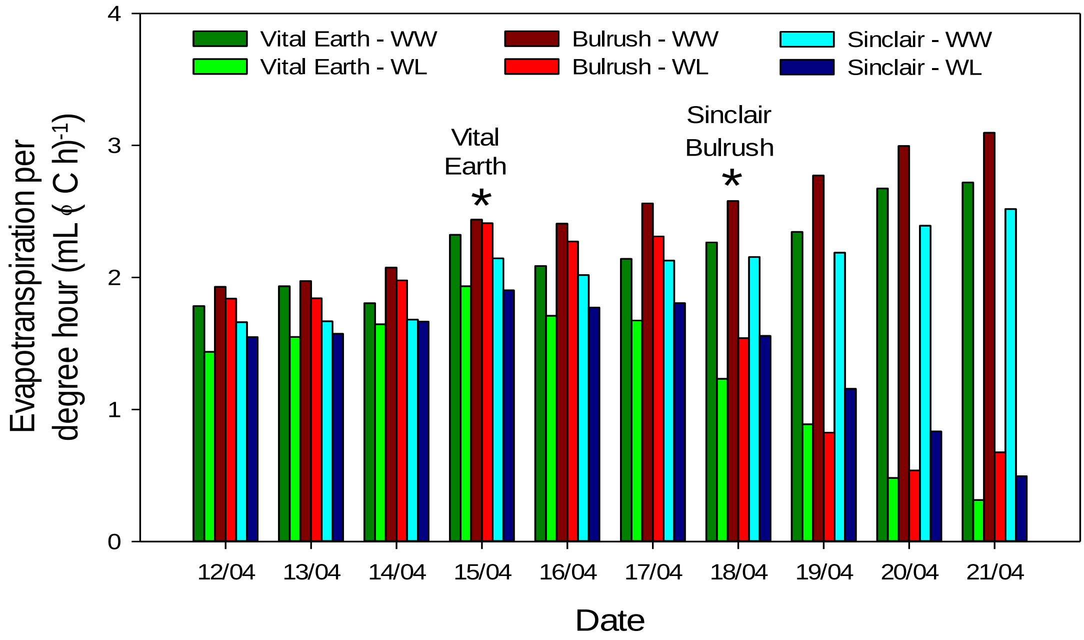

Figure GS5. Statistically significant differences in evapotranspiration between well-watered (WW) and water-limited (WL) treatments were first detected on April 15 for plants grown in Vital Earth substrate and April 18 for *Ribes* plants grown in Bulrush and Sinclair substrates

The first signs of wilting were noticed on one or two plants in all substrates on 19 April 2011, and by 25 April 2011, all of the plants growing in Bulrush substrate, and 4 of the plants growing in each of the Vital Earth and Sinclair substrates had wilted (Figure GS6). Average plant heights on 27 April 2011 were 39, 38 and 39 cm in well-watered Vital Earth, Bulrush and Sinclair substrates, respectively. Average heights were reduced by 9, 23 and 2% in water-limited Vital Earth, Bulrush and Sinclair substrates, compared to well-watered values. No differences in overall plant quality were noted.

Figure GS6 Well-watered and water limited *Ribes* grown in A) Vital Earth, B) Bulrush and C) Sinclair substrates. Photos were taken on 27 April 2011

The optimum range of substrate moisture content lies between the VSMCs at the point when physiological responses are triggered (Table GS3) and pot capacity.

Table GS3. *Ribes* plant-and-pot weights and VSMC for each of the three substrates when significant differences in physiological responses were first detected in water-limited plants compared to well-watered plants. Results are means of six replicate plants with associated standard errors of the mean values

Physiological parameter	**Pot weights and VSMC when physiological response first detected**					
	Vital Earth		**Bulrush**		**Sinclair**	
	Weight (g)	**VSMC (m^3 m^{-3})**	**Weight (g)**	**VSMC (m^3 m^{-3})**	**Weight (g)**	**VSMC (m^3 m^{-3})**
Stomatal conductance	1010 ± 40	0.198 ± 0.01	718 ± 24	0.136 ± 0.01	813 ± 43	0.146 ± 0.01
Whole-plant transpiration	1153 ± 30	0.260 ± 0.02	718 ± 24	0.136 ± 0.01	921 ± 55	0.192 ± 0.03
Evapotranspiration per degree hour	1153 ± 30	0.260 ± 0.02	718 ± 24	0.136 ± 0.01	921 ± 55	0.192 ± 0.03
Leaf extension	718 ± 14	0.112 ± 0.01	594 ± 12	0.110 ± 0.004	643 ± 12	0.106 ± 0.003

As for *Sidalcea*, in order to accommodate the logistical constraints to irrigation scheduling that occur during commercial production the VSMC recorded 24 h before the initiation of the most sensitive response was used as the lower irrigation set point (Table GS4). Corresponding plant-and-pot weights are also presented.

Table GS4. The range of optimum values for plant-and-pot weights and VSMCs for *Ribes* grown in each of the three substrates in 2 L pots. Results are means of seven replicate plants (pot capacity) and six replicate plants (Lower pot weight).

Substrate	**Optimum plant-and-pot weights and VSMCs for each substrate**			
	Pot weight (g)		**VSMC (m^3 m^{-3})**	
	Pot capacity	**Lower**	**Pot capacity**	**Lower**
Sinclair	1405	1000	0.49	0.21
Bulrush	1335	820	0.48	0.16
Vital Earth	1380	1205	0.43	0.30

Escallonia

Physiological responses to substrate drying were detected in *Escallonia* plants growing in all substrates on the same date, indicated by a significant decrease in stomatal conductance and transpirational water loss (Figure GS7).

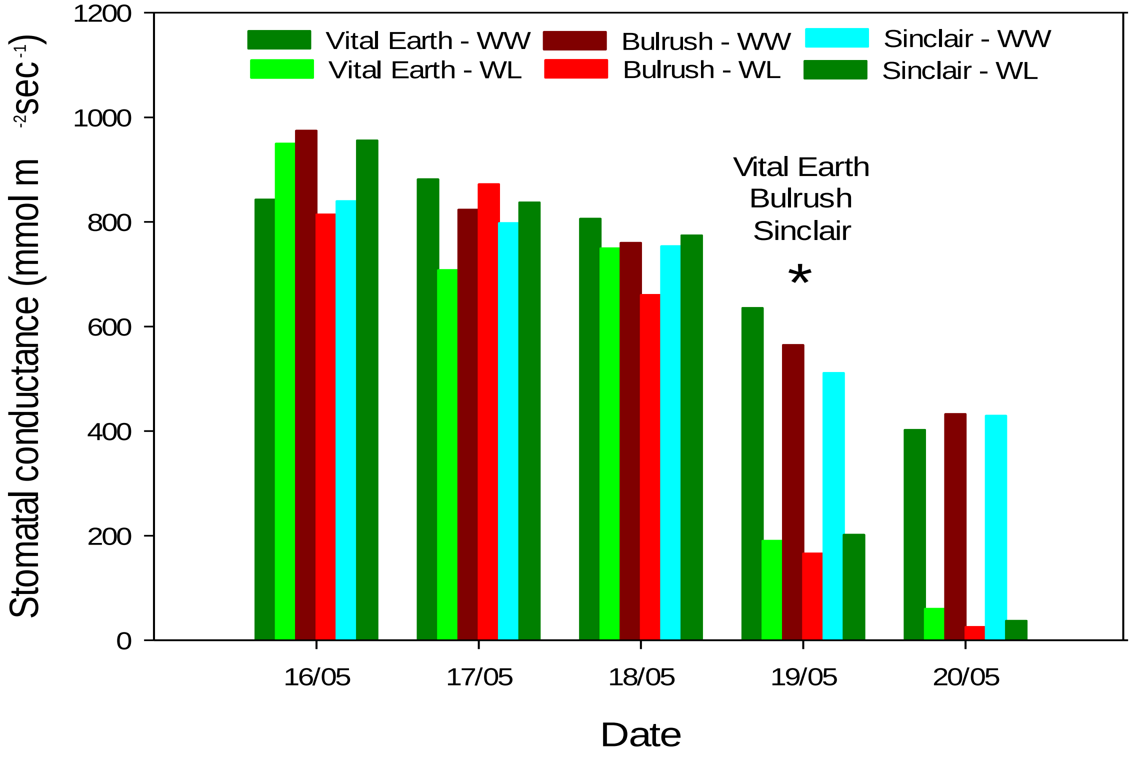

Figure GS7. Statistically significant differences in stomatal conductance between well-watered (WW) and water-limited (WL) treatments were first detected on May 19 for *Escallonia* plants grown in all substrates

The first signs of wilting were noticed in 4, 5 and 4 of the plants in Vital Earth, Bulrush and Sinclair substrates respectively on 19 May 2011, and by 25 May all of the plants in each substrate had wilted (Figure GS8).

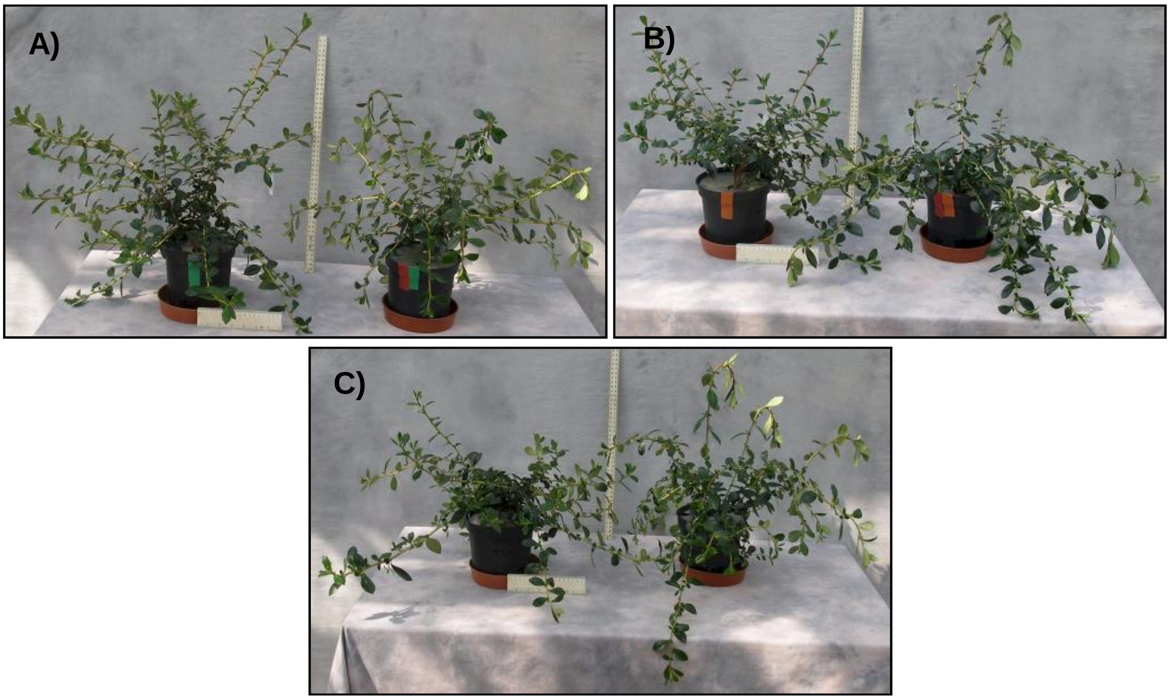

Figure GS8. Well-watered and water limited *Escallonia* grown in A) Vital Earth, B) Bulrush and C) Sinclair substrates. Photos were taken on 19 April 2011

Average plant spread on 23 May 2011 was 84, 87 and 85 cm in well-watered Vital Earth, Bulrush and Sinclair substrates, respectively. Average spreads were reduced by 11, 0 and 6% in water-limited Vital Earth, Bulrush and Sinclair substrates, compared to well-watered values. No differences in overall plant quality were noted.

The optimum range of substrate moisture content lies between the VSMCs at the point when physiological responses are triggered (Table GS5) and pot capacity. As for *Sidalcea* and *Ribes,* the VSMC recorded 24 h before the initiation of the most sensitive response was used as the lower irrigation set point (Table GS6). Corresponding plant-and-pot weights are also presented.

Table GS5. *Escallonia* plant-and-pot weights and VSMC for each of the three substrates when significant differences in physiological responses were first detected in water-limited plants compared to well-watered plants. Results are means of seven replicate plants with associated standard errors of the mean values

Physiological parameter	Pot weights and VSMC when physiological response first detected					
	Vital Earth		Bulrush		Sinclair	
	Weight (g)	VSMC ($m^3\ m^{-3}$)	Weight (g)	VSMC ($m^3\ m^{-3}$)	Weight (g)	VSMC ($m^3\ m^{-3}$)
Stomatal conductance	903 ± 19	0.210 ± 0.01	811 ± 34	0.196 ± 0.01	856 ± 22	0.187 ± 0.01
Whole-plant transpiration	903 ± 19	0.210 ± 0.01	811 ± 34	0.196 ± 0.01	856 ± 22	0.187 ± 0.01
Evapotranspiration per degree hour	903 ± 19	0.210 ± 0.01	811 ± 34	0.196 ± 0.01	856 ± 22	0.187 ± 0.01
Leaf extension	-	-	673 ± 22	0.128 ± 0.01	689 ± 14	0.125 ± 0.005

Table GS6. The range of optimum values for plant-and-pot weights and VSMCs for *Escallonia* grown in each of the three substrates. Results are means of seven replicate plants

Substrate	Optimum plant-and-pot weights and VSMCs for each substrate			
	Pot weight (g)		VSMC ($m^3\ m^{-3}$)	
	Pot capacity	Lower	Pot capacity	Lower
Vital Earth	1335	1010	0.50	0.25
Bulrush	1320	940	0.55	0.24
Sinclair	1455	1015	0.55	0.32

For the three substrates used in this project, the set points should be appropriate for use with plants of different ages/sizes and for plants grown indoors or outdoors. Although the pot weight threshold value will depend on pot size, the VSMC values should be similar in pots of different sizes for the same growing media. However, care needs to be taken when applying the values to different growing media as, even if the blend is similar, the physical characteristics (e.g. bulk density) could be significantly different. Practical advice for using trigger values for growing media with different physical characteristics will be developed during the project.

These values will be used in Year 2 in experiments on the East Malling Water Centre (EMWC) to optimise scheduling of irrigation (frequency and duration) to each substrate to match crop demand. The effects of the different substrates on plant quality will be determined using criteria developed by the project steering group.

Financial benefits

Full cost-benefit analyses at commercial nurseries would be required to quantify precisely the potential financial benefits arising from this project. However, significant cost savings are anticipated due to lowered production costs, more efficient use of resources and reduced plant wastage.

Figures provided by Will George (ADAS consultant), from the Horticultural Trade Association's Nursery Business Improvement Scheme (NBIS) suggest that the average value of plant waste from five nurseries during the period 2002 – 2004 was between £21,000 - £27,000 per annum or between 7 and 10% of turnover. Poor watering of peat-based growing media accounted for 3.2% of the waste, which equates with a loss of approximately £1,000 for each nursery per year. This particular project aims to minimise losses through poor watering during the transition to reduced-peat and peat-free substrates which could be much more substantial than those reported for peat-based media.

For those growers using mains water, scheduling irrigation effectively to match demand with supply to achieve modest water savings of 25% could also reduce average water bills by £1,410 per year (based on figures supplied from NBIS for 2006-2007).

Action points for growers

The emphasis in the first project year has been on developing a robust and reliable approach to determine the optimum moisture contents for the three substrates. Following trials on the EMWC in 2011, action points for growers will be included in the next annual report.

SCIENCE SECTION

Introduction

The HNS sector is the largest user of peat in the UK horticultural industry[1]. Around 450,000 m^3 of growing medium, of which about 80% is peat, is used annually for hardy nursery stock production in the UK[2]. Although some customers request peat-free production (*e.g*. The National Trust), the majority do not and so at the moment, there is little commercial pressure to reduce peat use. However, the UK government is committed to reducing peat use under the Biodiversity Action Programme, and the target for 2010 was to ensure that 90% of total market requirements for soil improvers and growing media should be supplied by non-peat materials. The 2010 target proved challenging and was not achieved; however new targets of 2015 for the government and public sector and 2030 for the professional horticulture and landscaping sectors have been proposed, as outlined in Defra's consultation document published in December 2010[3] ('Consultation on reducing the horticultural use of peat in England 2010'). The proposed withdrawal of peat from the UK horticulture industry is of great concern to many HNS growers.

Recent research[4] has shown that growing HNS in even 100% alternatives to peat, such as coconut fibres or pine bark, can be as successful in terms of resulting in the same plant growth and quality as produced in peat. There are potential advantages from using reduced-peat growing media which are not currently being exploited due to concerns about how best to manage irrigation and fertigation regimes. For example, rooting is often improved in better draining media and the drier surface reduces moss and liverwort growth, which could help to reduce labour costs associated with the preparation of plants for dispatch. The impact of over-watering on crop losses and plant quality is likely to be lower when using reduced-peat media, as are losses due to root death caused by over-wet substrates during winter.

A major reason for the limited uptake of non-peat substrates by HNS growers is a lack of confidence in how to manage peat alternatives. This includes uncertainty with respect to irrigation and nutrition[4]. The relatively poor water-holding capacity of most peat-free alternatives will necessitate more frequent irrigation events but over-watering must be avoided to minimise run-through of water and dissolved fertilisers and limit environmental pollution. The need to irrigate commercial crops is often judged by visual assessment. The colour of peat changes from dark to light brown when dry, but with reduced peat or peat-free substrates, the top layer tends to dry out very quickly (increasingly so, the higher the percentage replacement). As a result, reduced peat or peat-free substrates are often over-watered, as they appear to be drying out when in fact lower layers are still wet. To help facilitate the development of 'best' or 'better' grower practice during the transition to peat-free production, new experimentally-derived irrigation set points are needed that maintain an optimum substrate moisture content for the reduced peat and peat-free media likely to be used by HNS growers in the future.

Over-watering can also lead to nutrient leaching, particularly nitrates and phosphates, which is both wasteful and environmentally undesirable. Peat alternatives do not necessarily have the same capacity to retain nutrients as peat, and the most commonly used system of nutrition in HNS production, Controlled Release Fertilisers (CRFs), was developed for peat. The ratios of N:P:K available have also been designed for use in peat substrates. This, coupled with over-watering, can lead to poor plant nutrition. It is likely that specific fertiliser regimes will need to be developed for reduced peat and peat-free substrates. This work will be important to optimise crop quality but is beyond the scope of this initial project

In this project, the 'optimum' substrate moisture content is defined as one that supports good, healthy plant growth while avoiding over-wet conditions so that leaching of irrigation water and fertilisers is minimised or eliminated. To identify the optimum range of substrate moisture contents, our approach was to first determine VSMC at 'pot capacity' then impose gradual substrate drying on half of the plants and monitor physiological responses such as stomatal conductance, transpiration rate and leaf extension growth. Irrigation set points will be identified for each substrate and used to develop new guidelines to help growers overcome problems associated with over-watering reduced peat and peat-free alternatives. This approach has been used very successfully to identify irrigation set points for field-grown strawberry production and water savings (and fertiliser) savings of 40% have been delivered in commercial field trials[5].

The overall aim of the project is to develop and implement improved irrigation scheduling guidelines for reduced peat, peat-free and industry standard media to help growers comply with legislation, optimise plant quality, reduce costs and gain confidence in growing HNS in peat alternatives. Despite much recent research into irrigation scheduling for the HNS sector at EMR[6,7] and elsewhere, uptake of the work by the industry has been limited and irrigation of industry standard substrates remains largely unscheduled. Consequently, industry water and fertiliser use efficiencies are often low, with associated losses of water and nutrients and lowered plant quality. It will be important to ensure that this project delivers practical solutions that fulfil the sector's requirements. Constructive advice and support from the project steering group (which consists of key growers, consultants and advisors) will help to achieve this goal.

Materials and methods

Industry standard, reduced peat and peat-free substrates

The following substrates were chosen after consultation with the project steering group; the reason for choice of brand was that these substrates are (or are becoming) widely used by UK growers:

- **Industry standard:** substrate based on 25% bark, 75% peat supplied by Sinclair
- **Reduced peat:** substrate based on 25% wood fibre, 25% bark, 50% peat supplied by Bulrush
- **Peat free:** substrate based on peat-free materials (composted green waste and bark) supplied by Vital Earth

Specification details were obtained for each substrate; a sample of each was also sent to NRM Ltd (Bracknell, Berkshire) in February 2011 for analysis of air-filled porosity, particle size distribution, pH, density, dry matter, dry density, Ca, Cl, Mg, P, K, Na, N, EC and trace elements. The results of these analyses are presented in Appendix I (Tables A1, A2). For the Vital Earth substrate, additional data was obtained for water soluble nitrogen, pH and EC for December 2010 and January 2011 (analysis performed for Vital Earth Ltd by Alliance Technical Laboratories Ltd, Ipswich, Suffolk) to demonstrate the mineralisation ("slow release") of N in this substrate; these results are presented in Appendix 1, Table A3.

Plant material and growth conditions

Experimental plant species were selected after consultation with the project steering group. The following widely-produced crops were chosen as they are moderately resilient to substrate drying and so were considered a good choice of 'indicator' species:

- *Sidalcea oregana* 'Party Girl'
- *Ribes sanguineum* 'Koja'
- *Escallonia rubra* 'Crimson Spire'

Fifty bare-rooted *Sidalcea* were supplied by Howard Nurseries (Diss, Norfolk, UK) and fifty 9 cm liners of *Ribes* and *Escallonia* were supplied by New Place Nursery (Pulborough, West Sussex, UK). Plants were graded to help ensure that variability was spread evenly between different treatments and that each experimental block contained plants of equivalent grade. *Sidalcea* were divided in to three grades based on the number of basal breaks - high medium and low. *Escallonia* and *Ribes* were divided into two grades – 'well-branched' and 'less well-branched'. *Sidalcea* roots were trimmed to 60 mm length before potting and in *Ribes* and *Escallonia,* the bottom 20 mm of compost was gently removed to leave a root ball of about 60 mm. Plants were potted in to 2 L pots containing one of the three commercially available substrates. Controlled release fertiliser (Osmocote Pro 12-14 month, 18+9+10 +2 MgO + trace elements) was incorporated at 3 kg per 1000 L for *Sidalcea* and 5 kg per 1000 L for *Ribes* and *Escallonia*. All plants were grown on in two glasshouse compartments maintained at 15 / 10 ºC (day / night) with supplementary lighting supplied from sodium lamps during a 12 h photoperiod; relative humidity was uncontrolled. Plants were hand-watered during establishment. A polythene disc was placed around the base of all plants, on top of the compost, to minimize evaporation from the substrate surface so that transpirational water loss could be measured accurately. To establish irrigation set points a controlled environment is required, therefore the plants were maintained under glass for the duration of the experiment.

Once new growth had commenced (after about three weeks), *Sidalcea* stems from the previous year were cut back to ~25 mm above the substrate surface. *Ribes and Escallonia* plants were shaped after eight weeks by trimming back tips of the most vigorous shoots. Experiments commenced once the root system and canopy were sufficiently developed and plants were transpiring freely; in March 2011 *Sidalcea* plants had reached this stage (Figure 1A), and experiments with *Ribes* and with *Escallonia* (Figure 1B and C) were scheduled to begin in April and May 2011 when plants reached a sufficient size to be able to dry down the substrate fairly rapidly once irrigation volumes were reduced.

Figure 1. Well-watered A) *Sidalcea oregano,* B) *Ribes sanguineum* and C) *Escallonia rubra* plants in 2L pots containing peat-free (Vital Earth), reduced peat (Bulrush) or industry standard substrate (Sinclair) in glasshouse compartments at EMR. Photo A) was taken on 14 March; photos B) and C) were taken on 29 March 2011

Experimental design

Two treatments were imposed on plants growing in each of the three substrates; a well-watered (WW) control in which irrigation was scheduled to match demand with supply and a water-limited (WL) treatment in which the substrates were allowed to dry down (see below). A complete randomized block design was used with eight experimental blocks, each containing six plants. Each substrate and each treatment were represented in each block; there were eight replicate plants per treatment.

Irrigation application and scheduling

The timing and duration of irrigation events was controlled using three Galcon DC-4S units (supplied by City Irrigation Ltd, Bromley, UK) connected to manifolds housing three DC-4S ¾" valves. Water was sourced from the mains and irrigation was supplied to each pot *via* a dripper stake and bootlace connected to a pressure compensated 2 L h^{-1} emitter. Dripper outputs were tested prior to the experiment to ensure an accuracy of within 5% of the mean; outputs were then monitored at weekly intervals throughout the experiment. The frequency and duration of daily irrigation events was adjusted throughout the experiment to ensure that run-through was minimised as plant water demand, and therefore irrigation volume, increased. Irrigation scheduling was first applied to *Sidalcea* on 8 February 2011 and to *Ribes* and *Escallonia* on 11 March. Potential evapotranspiration (*ETp*) values were obtained using an SKTS 500/PRT Evaposensor and SEM 550 Evapometer (Skye Instruments Limited, Llandrindod Wells, Powys, UK). The Evaposensor was positioned at canopy height amongst the experimental plants (Figure 2).

Figure 2. The Skye EvapoSensor and EvapoMeter were used to estimate daily evapotranspiration. Photo taken on 14 March 2011

Determining crop coefficients

To calculate the appropriate amount of irrigation water to apply to each substrate, separate crop coefficients that related gravimetric estimates of plant water loss to the accumulated *ETp* over 24 h were calculated every week for each substrate. Water loss per degree hour was determined and used in conjunction with the number of daily degree hours in the previous 24 h to determine the average daily volume of water used by the plants. Thus, the sum total volume of the daily irrigation events replaced the volume of water estimated to have been lost during the previous 24 h.

Imposition of substrate drying treatment

The substrate drying treatment was first imposed on 15 March (*Sidalcea*), 12 April (*Ribes*) and 16 May (*Escallonia*) 2011. At this stage, WW plants received two irrigations per day. Drippers were removed from the WL pots (and subsequently replaced) so that one irrigation event was missed; in this way the WL pots received 50% of the water applied to WW pots. The rate of substrate drying decreased as *Sidalcea* and *Ribes* plants in the WL treatment adapted to the stress and so the volume of water applied was reduced to 33% of that applied to WW plants on 21 March (*Sidalcea*) and 18 April (*Ribes*) 2011. In order to be able to identify the permanent wilting point, irrigation was withheld from the WL pots on 25 March (*Sidalcea*), 21 April (*Ribes*) and 20 May (*Escallonia*) 2011.

Volumetric substrate moisture content

Daily measurements of VSMC were made in blocks 1-7 with a Delta-T 'WET' sensor which was calibrated for each substrate. To determine the average VSMC within each pot, four sets of holes were drilled in the sides of each pot to allow the horizontal insertion of the 'WET' sensor probe. The upper sets were drilled 30 mm down from pot shoulder and the lower sets 20 mm up from pot base and the average pot VSMC was determined.

Decagon 10HS sensors connected to Decagon EM50 data loggers were used to make continuous measurements of substrate VSMC in block 8. The sensors were calibrated for each substrate (Figure 3) and the resulting regression equation was used to convert raw probe counts into VSMC. A horizontal slit was cut in one side of the pot 60 mm down from pot shoulder to allow insertion of the 10HS probe and the root ball or root system of the plant was placed on top of the probe before filling the pot with substrate.

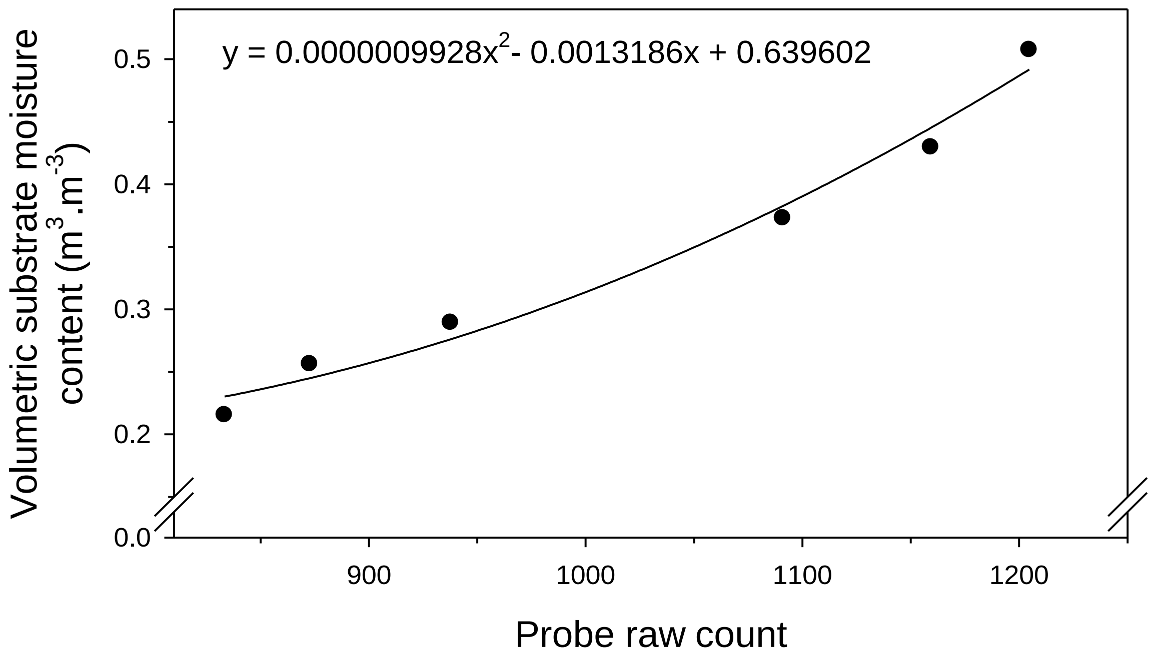

Figure 3. Calibration of the 10HS probe for the industry standard (Sinclair) substrate. The regression equation was used to convert raw probe counts (mV) into VSMC

Physiological responses to substrate drying

Physiological responses to decreasing VSMC were measured daily using plants in blocks 1-7, 30 min after the first irrigation event. Transpirational water loss (*E*) was determined gravimetrically between 09:30 and 12:30; VSMC was measured at 09:30 and stomatal conductances (g_s) of fully expanded leaves three or four nodes from the apex of a floral spike were measured between 11:30-12:30 using a leaf porometer (Decagon Devices). The rate of vegetative growth for each plant was recorded by measuring petiole length and leaf length for a selected apical unfurling, expanding leaf on a floral stem. Plant height measurements were made at the beginning and end of the substrate drying period. It was not possible to measure leaf water potential in *Sidalcea* due to the absence of secondary thickening and the angular, hollow nature of the petiole; the applied pressure at which xylem sap first appeared at the cut petiole surface could not be determined. Leaf water potential was recorded for *Ribes* on 12, 15, 18, 19, 20 and 21 April and for *Escallonia* plants on 17 and 23 May. The time that leaf wilting first occurred was recorded and the degree of leaf wilting at 12:30 was then scored on a scale of 0 (no wilting) to 3 (severe wilting).

Statistical analyses

Statistical analyses were carried out using GenStat 10th Edition (VSN International Ltd.). To determine whether differences between treatments were statistically significant, analysis of variance (ANOVA) tests were carried out and least significant difference (LSD) values for $P \leq 0.05$ were calculated.

Results

Irrigation scheduling

The irrigation scheduling approach using daily estimates of *ETp* in conjunction with crop co-efficients effectively maintained WW plant-and-pot weights within a very narrow range for each substrate during the experiment (Figures 4A, 5A and 6A). Run-through from the pots was generally less than 5% of the total irrigation volume applied (data not shown). Plant-and-pot weighs at pot capacity were higher for the Sinclair (industry standard) substrate than for the Vital Earth (peat-free) and Bulrush (reduced peat). This was presumably due to the lower air-filled porosity of the Sinclair substrate (Appendix I, Table A2).

Once the substrate drying treatment was imposed, plant-and-pot weights fell gradually. Significant differences in plant-and-pot weights between WW and WL treatments were first detected for *Sidalcea* on 17 March in the Sinclair substrate and on 18 March for the Vital Earth and Bulrush substrates, for *Ribes* on 15 April in the Vital Earth substrate and on 18 April for the Bulrush and Sinclair substrates, and for *Escallonia* on 19 May for all three substrates. The plant-and-pot weights at which physiological responses to drying substrate were first detected are indicated by arrows (Figures 4A, 5A and 6A).

Volumetric substrate moisture contents were also maintained within acceptable limits in the WW substrates although values gradually fell during the experiment (Figure 4B, 5B and 6B). Since plant and pot weights remained constant, this was presumably a consequence of repeated measurements using the WET sensor probe which may have caused localised substrate drying. Values of VSMC at pot capacity were significantly higher for Bulrush and Sinclair substrates than those of the Vital Earth substrate. Changes in VSMC in the WL substrates were similar to those described for plant-and-pot weights. The VSMC at which physiological responses to drying substrate were first detected are indicated by arrows (Figure 4B, 5B and 6B).

Changes in VSMC were also measured continuously with Decagon 10HS substrate moisture probes (Figure 7) and the two or three daily irrigations to the WW pot were detected. Values in the WW treatment were similar to those obtained with Delta-T WET sensor but the dynamics of changes in VSMC during the drying down phase differed. This was presumably due to differences in relative rates of water loss due to variation in plant canopy area between the plant growing in the pot with the Decagon probe and the average plant canopy area.

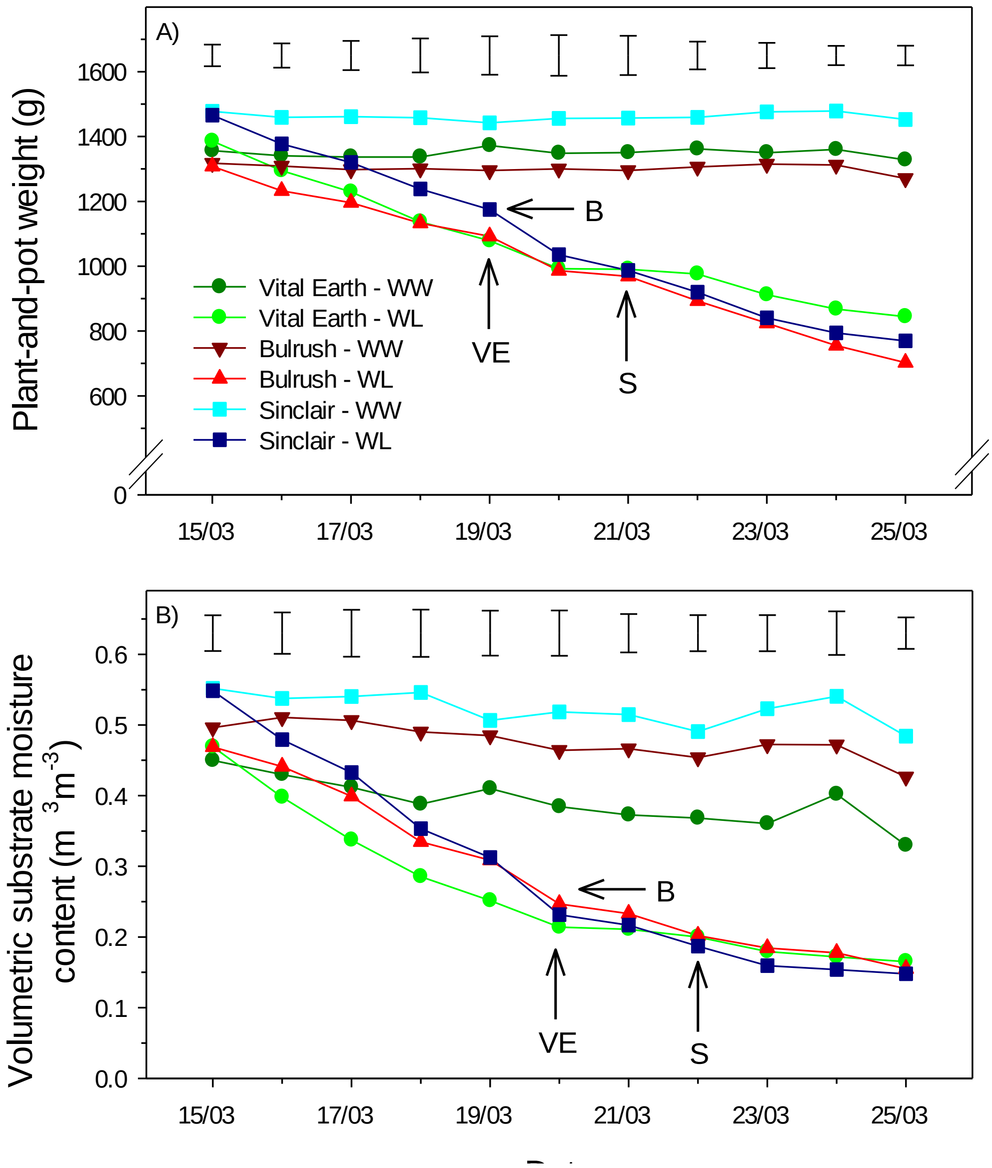

Figure 4. Changes in A) plant-and-pot weights and B) VSMC of potted *Sidalcea* plants grown in peat-free (Vital Earth), reduced peat (Bulrush) and industry standard (Sinclair) substrates under well-watered (WW) or water-limited (WL) conditions. Arrows indicate when physiological responses were first detected. Results are means of seven replicate plants; LSD values are for $P \leq 0.05$ with 30 degrees of freedom

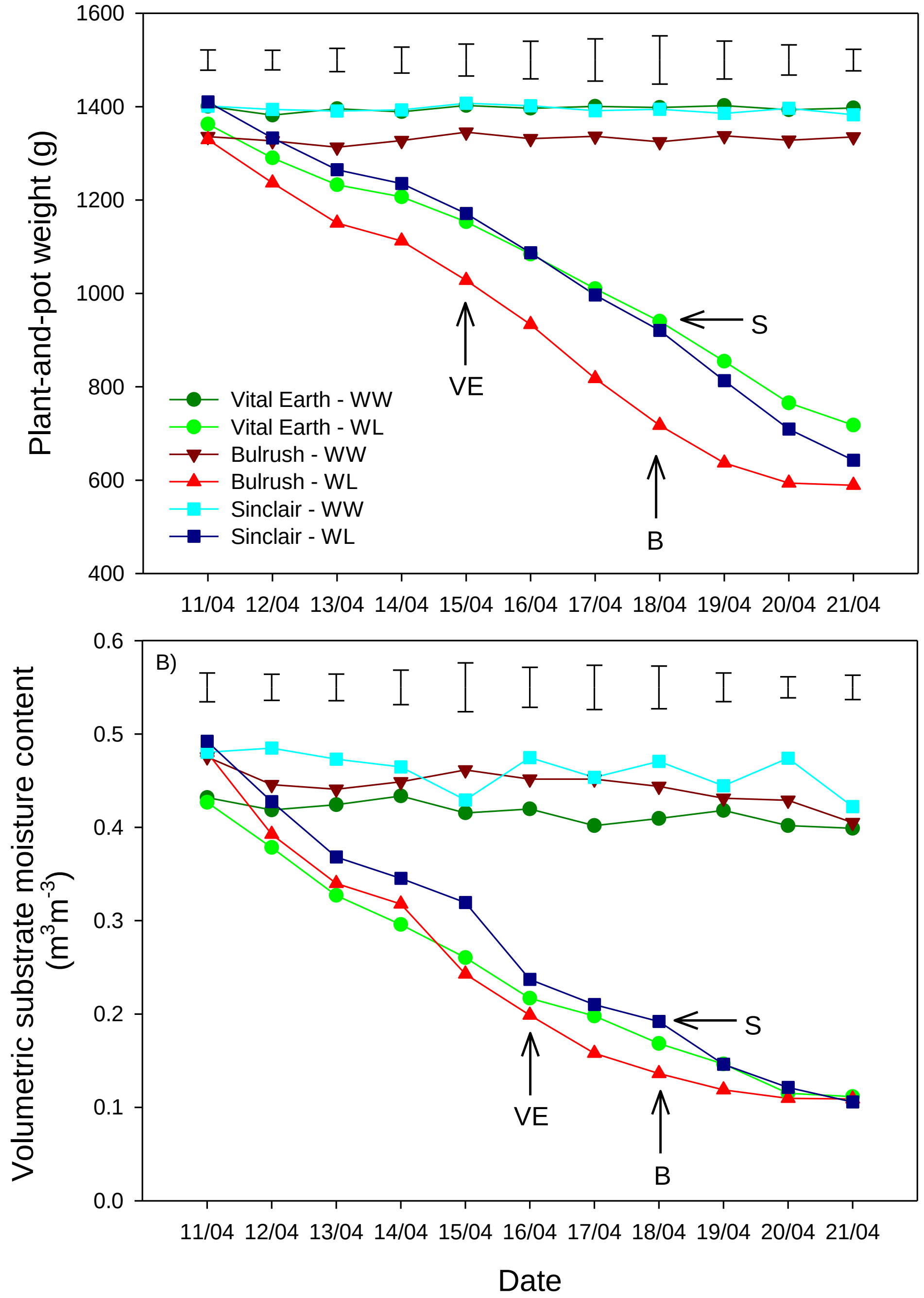

Figure 5. Changes in A) plant-and-pot weights and B) VSMC of potted *Ribes* plants grown in peat-free (Vital Earth), reduced peat (Bulrush) and industry standard (Sinclair) substrates under well-watered (WW) or water-limited (WL) conditions. Arrows indicate when physiological responses were first detected. Results are means of seven replicate plants (WW) and six replicate plants (WL); LSD values are for *P*≤0.05 with 26 degrees of freedom

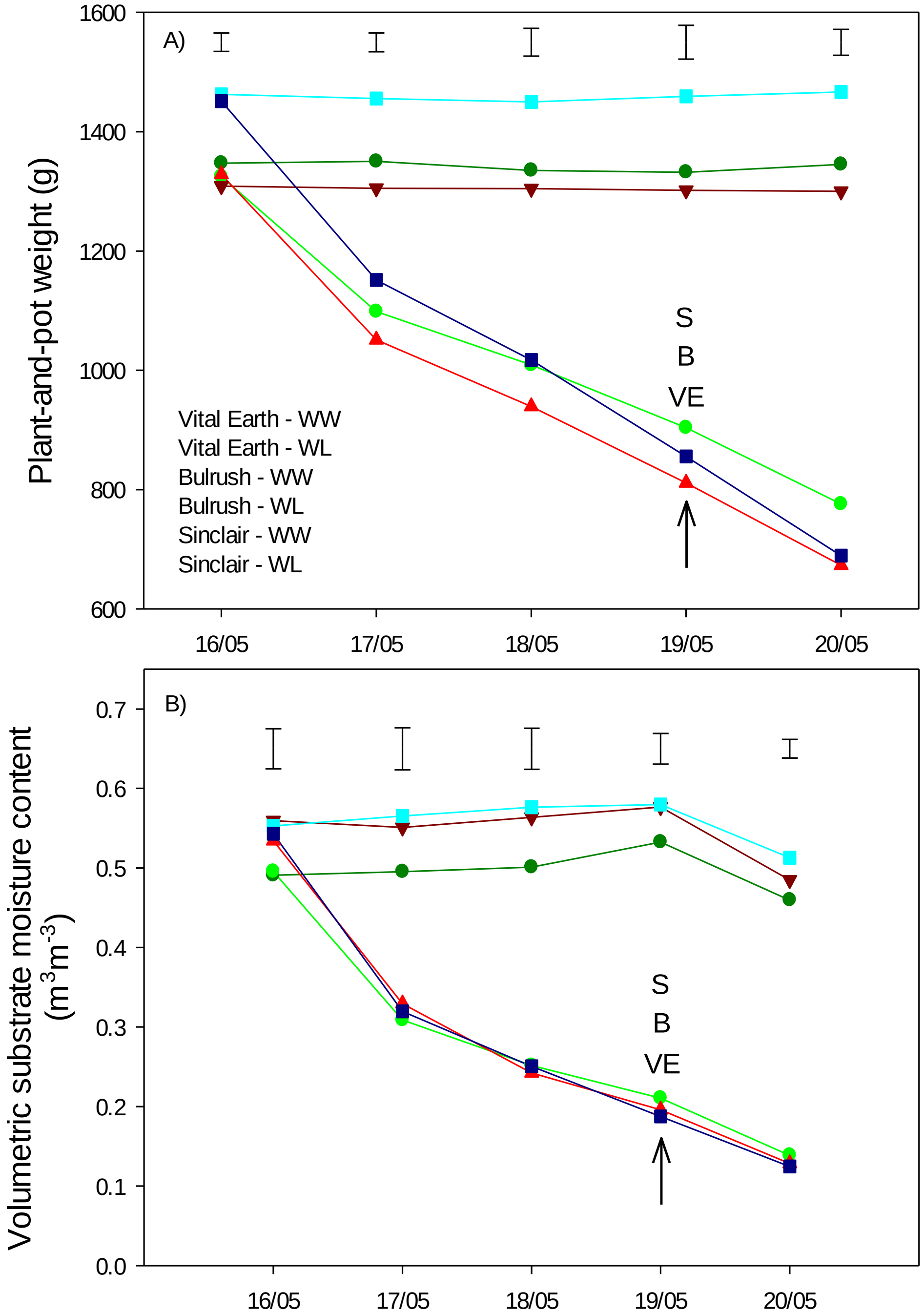

Figure 6. Changes in A) plant-and-pot weights and B) VSMC of potted *Escallonia* plants grown in peat-free (Vital Earth), reduced peat (Bulrush) and industry standard (Sinclair) substrates under well-watered (WW) or water-limited (WL) conditions. Arrows indicate when physiological responses were first detected for all three substrates. Results are means of seven replicate plants; LSD values are for $P \leq 0.05$ with 30 degrees of freedom

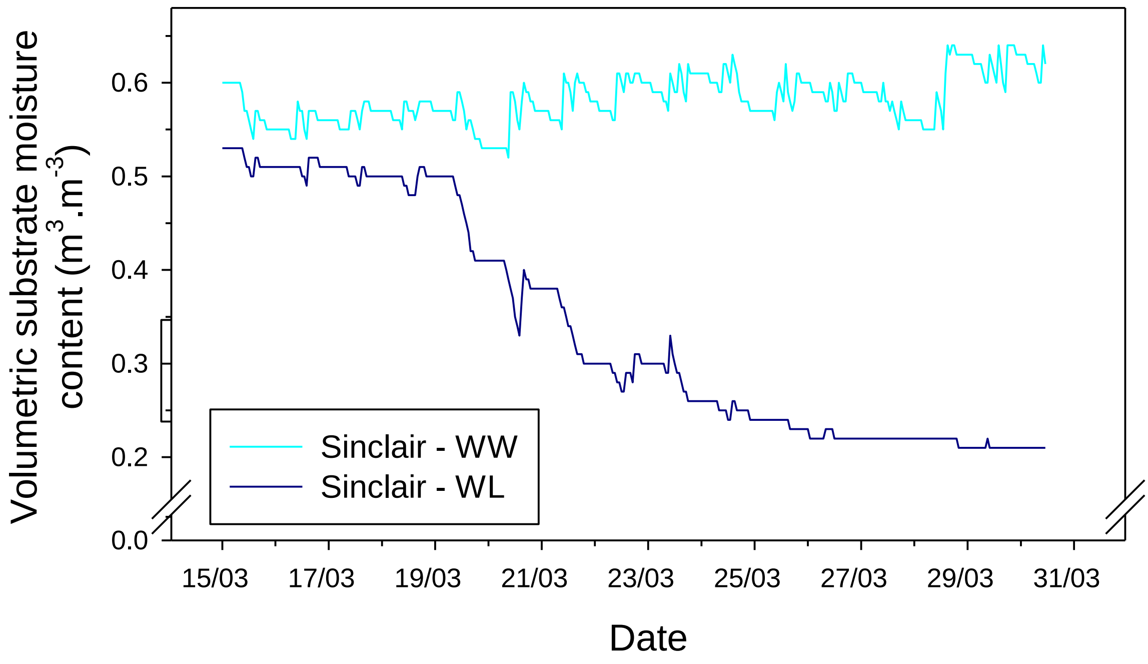

Figure 7. Changes in VSMC for *Sidalcea* plants growing in industry standard substrate (Sinclair) measured with Decagon 10HS probes under well-watered or water-limited conditions

Plant responses to drying substrate

Stomatal conductance (g_s) values of WW plants in each of the substrates varied with changes in ambient light intensity (Figure 8) but the relatively high values (≥ 500 mmol m^{-2} s^{-1}) indicated that all WW plants were transpiring freely and that soil water availability was optimal. Significant reductions in g_s of WL plants compared to WW plants, were first detected on 19, 20 and 22 March 2011 for *Sidalcea* WL plants grown in Vital Earth, Bulrush and Sinclair substrates, respectively (Figure 8A), on 17, 18 and 19 April 2011 for *Ribes* WL plants grown in Vital Earth, Bulrush and Sinclair substrates, respectively (Figure 8B), and on 19 May for *Escallonia* plants for all three substrates (Figure 8C). Stomata continued to close in response to the drying treatments and g_s was less than 10% of WW values in all substrates by the end of the *Sidalcea* and *Ribes* experiments and 25-30% of WW values in all substrates by the end of the *Escallonia* experiment.

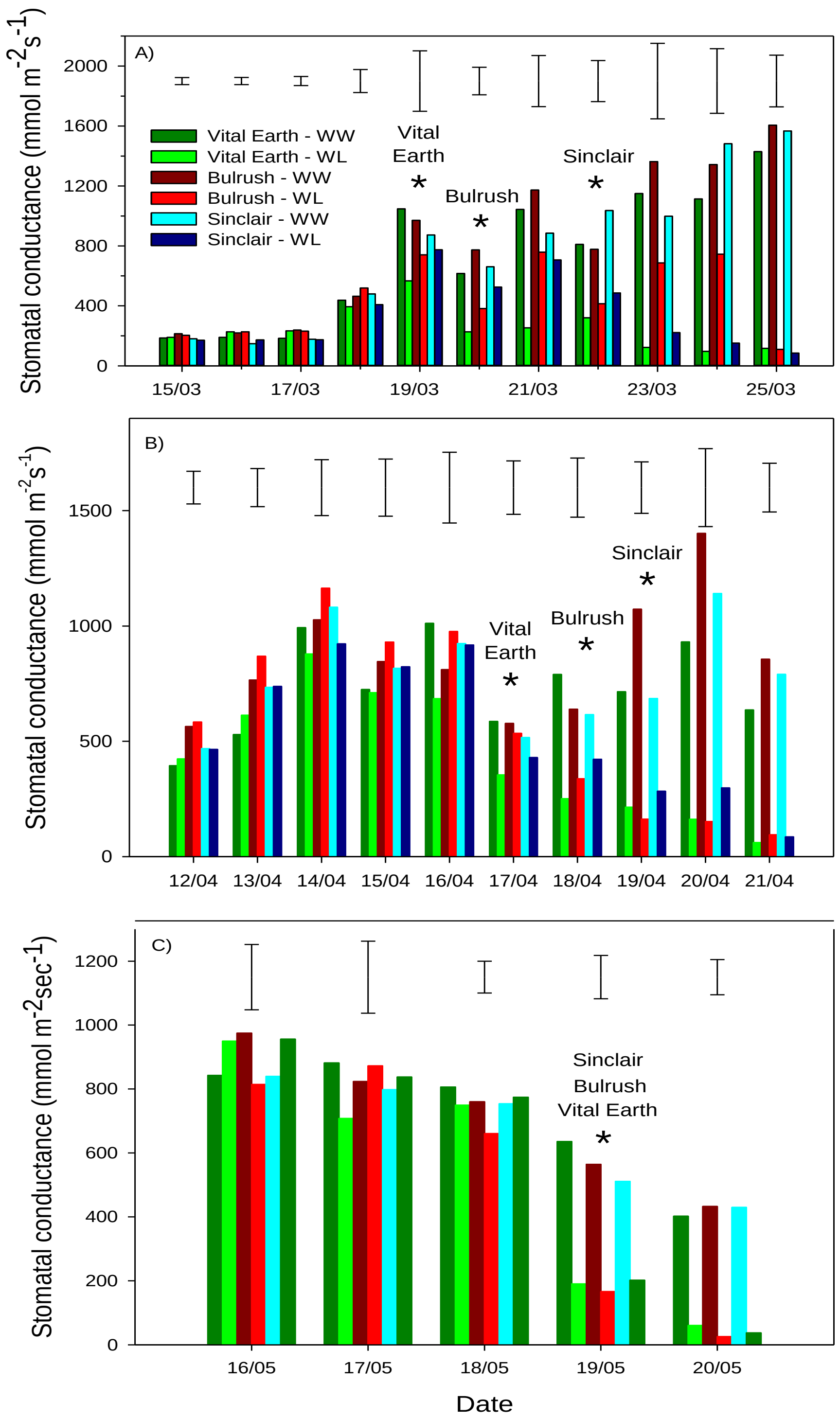

Figure 8. Changes in stomatal conductance of potted plants in peat-free (Vital Earth), reduced peat (Bulrush) and industry standard (Sinclair) substrates under well-watered or water-limited conditions, for A) *Sidalcea*, B) *Ribes* and C) *Escallonia*. Asterisks indicate when physiological responses were first detected for all three substrates. Results are means of seven replicate plants (A and C) and six replicate plants (B); LSD values are for $P \leq 0.05$ with 30 degrees of freedom (A and C) and 26 degrees of freedom (B)

Since measures of *E* integrate the stomatal responses of all leaves, they too were influenced by changes in light intensity. For example, rates in *Sidalcea* WW plants were relatively slow during the overcast weather at the beginning of the experiment but increased during the sunny weather from the 19 March onwards. Significant differences in *E* between WW and WL treatments were first detected on 19 March for *Sidalcea* plants in Vital Earth and Bulrush substrates and on 21 March for those in the Sinclair substrate (Figure 9A). Significant differences in *E* between WW and WL *Ribes* plants were detected on 15 April for plants in Vital Earth and 18 April for plants in Bulrush and Sinclair substrates (Figure 10A). For all three substrates, significant differences between WW and WL *Escallonia* plants were detected on the same date, 19 May (Figure 11A). Differences in evaporative demand caused by variations in ambient conditions can be accounted for, at least in part, by calculating rates of evapotranspiration per degree h. Although these rates were more consistent in WW plants on different days, significant differences between WW and WL plants were detected on the same dates, and therefore the same VSMC, as for *E* (Figures 9B, 10B, 11B).

Petiole and leaf extension growth were also measured in the WW and WL treatments. Leaf growth is often the most sensitive indicator of drying substrate but in all three crops, the variable response of petiole and leaf extension in the WL plants meant that significant differences from WW values were not detected until several days after changes in g_s and *E* were first noted (Figures 12, 13, 14).

For *Ribes a* significant decrease in leaf water potential was first observed in plants growing in Bulrush substrate, on 18 April, and in Sinclair substrate on 19 April (Figure 15A). By 20 April significant differences had not been observed in plants growing in Vital Earth substrate. Leaf water potential was measured for *Escallonia* on 17 May and 23 May, when a significant decrease in leaf water potential was observed for plants growing in all three substrates (Figure 15B).

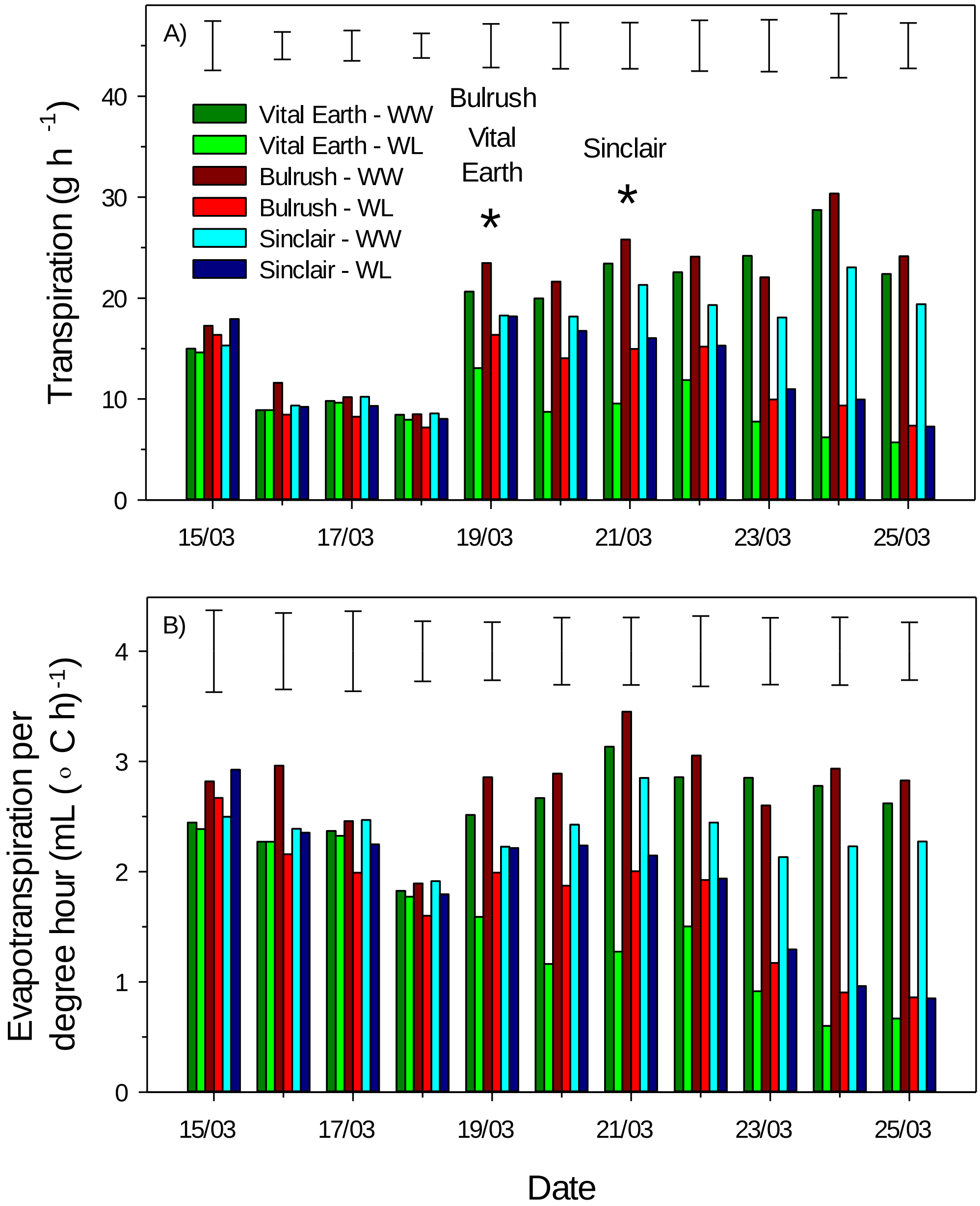

Figure 9. Changes in A) whole-plant transpiration rate and B) evapotranspiration per degree h of potted *Sidalcea* plants grown in peat-free (Vital Earth), reduced peat (Bulrush) and industry standard (Sinclair) substrates under well-watered or water-limited conditions. Asterisks indicate dates, which are the same for both A) and B), when physiological responses were first detected for all three substrates. Results are means of seven replicate plants; LSD values are for $P \leq 0.05$ with 30 degrees of freedom

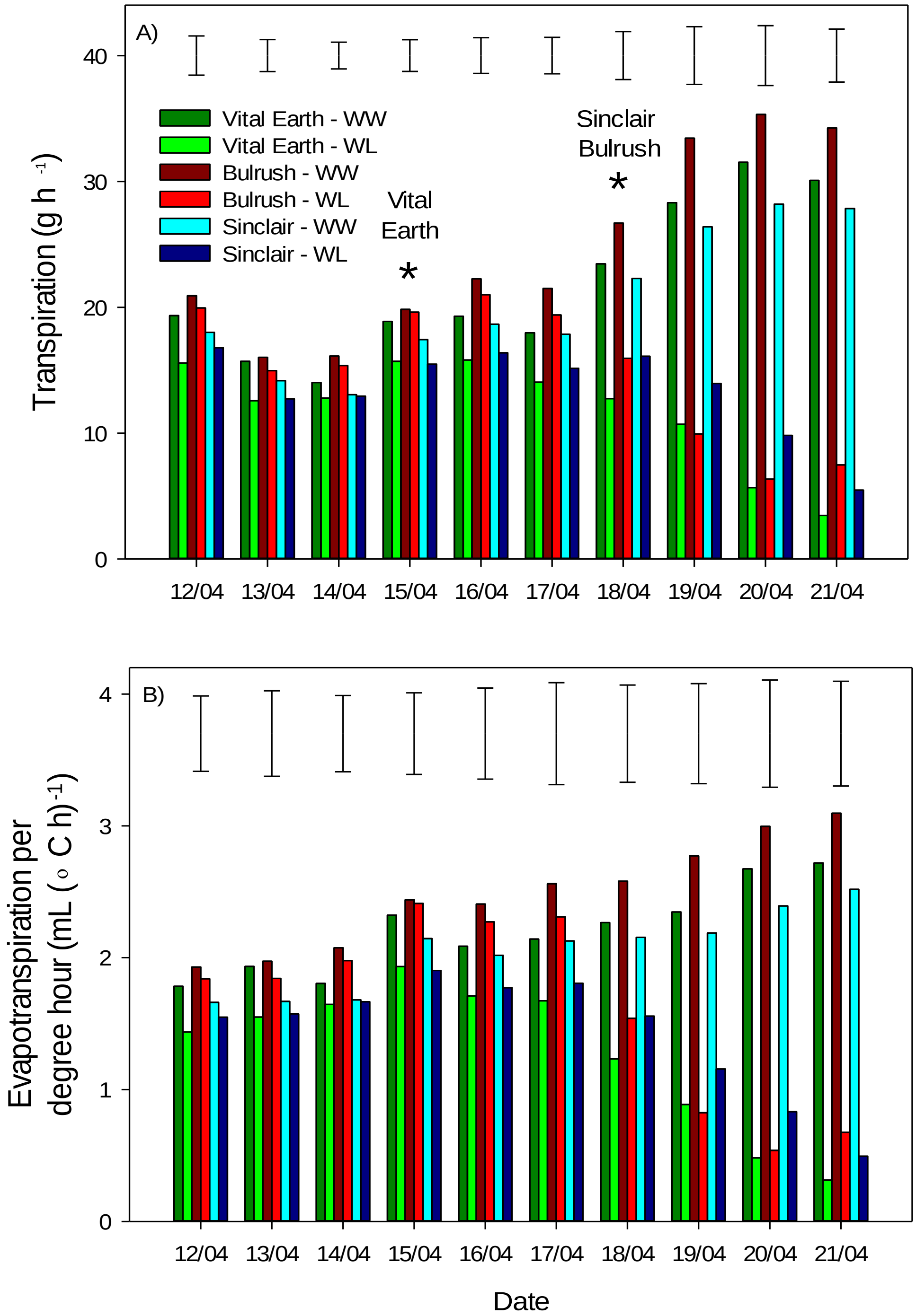

Figure 10. Changes in A) whole-plant transpiration rate and B) evapotranspiration per degree h of potted *Ribes* plants grown in peat-free (Vital Earth), reduced peat (Bulrush) and industry standard (Sinclair) substrates under well-watered or water-limited conditions. Asterisks indicate dates, which are the same for both A) and B), when physiological responses were first detected for all three substrates. Results are means of six replicate plants; LSD values are for $P \leq 0.05$ with 26 degrees of freedom

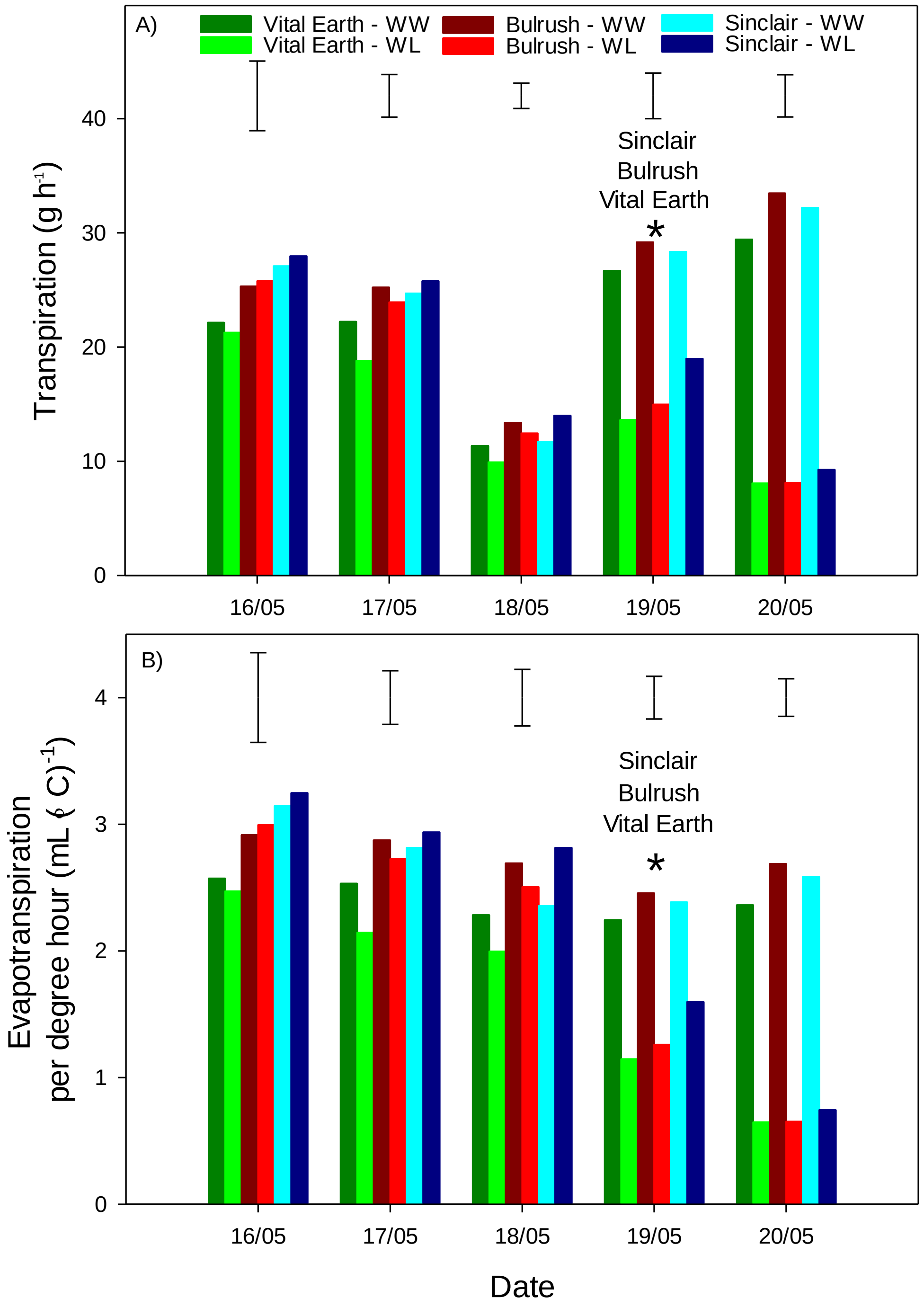

Figure 11. Changes in A) whole-plant transpiration rate and B) evapotranspiration per degree h of potted *Escallonia* plants grown in peat-free (Vital Earth), reduced peat (Bulrush) and industry standard (Sinclair) substrates under well-watered or water-limited conditions. Asterisk indicates date, which is the same for A) and B), when physiological responses were first detected for all three substrates. Results are means of seven replicate plants; LSD values are for $P \leq 0.05$ with 30 degrees of freedom

The onset of wilting in *Sidalcea* was delayed by one day in WL plants grown in the Sinclair substrate; first signs of wilting were noted on some plants in the Vital Earth and Bulrush substrates on 19 March 2011. By 21 March 2011, the extent of wilting was similar in all WL treatments and the degree of wilting continued to develop at similar rates thereafter (data not shown). Average plant heights on 29 March 2011 were 29, 30 and 27 cm in WW Vital Earth, Bulrush and Sinclair substrates, respectively. Average heights were reduced by 38, 40 and 4% in WL Vital Earth, Bulrush and Sinclair substrates, compared to WW values. For *Ribes* the first signs of wilting were noted on one or two plants in all substrates on 19 April 2011, and by 25 April 2011, all of the plants growing in Bulrush substrate, and 4 of the plants growing in each of the Vital Earth and Sinclair substrates had wilted. Average plant heights on 27 April 2011 were 39, 38 and 39 cm in well-watered Vital Earth, Bulrush and Sinclair substrates, respectively. Average heights were reduced by 9, 23 and 2% in water-limited Vital Earth, Bulrush and Sinclair substrates, compared to well-watered values. Wilting in *Escallonia* was first noted in 4, 5 and 4 of the plants in Vital Earth, Bulrush and Sinclair substrates on 19 May 2011 and by 25 May, all of the plants in each substrate had wilted (Figure GS4). Average plant spreads on 23 May 2011 were 84, 87 and 85 cm in well-watered Vital Earth, Bulrush and Sinclair substrates, respectively. Average spreads were reduced by 11, 0 and 6% in water-limited Vital Earth, Bulrush and Sinclair substrates, respectively, compared to well-watered values.

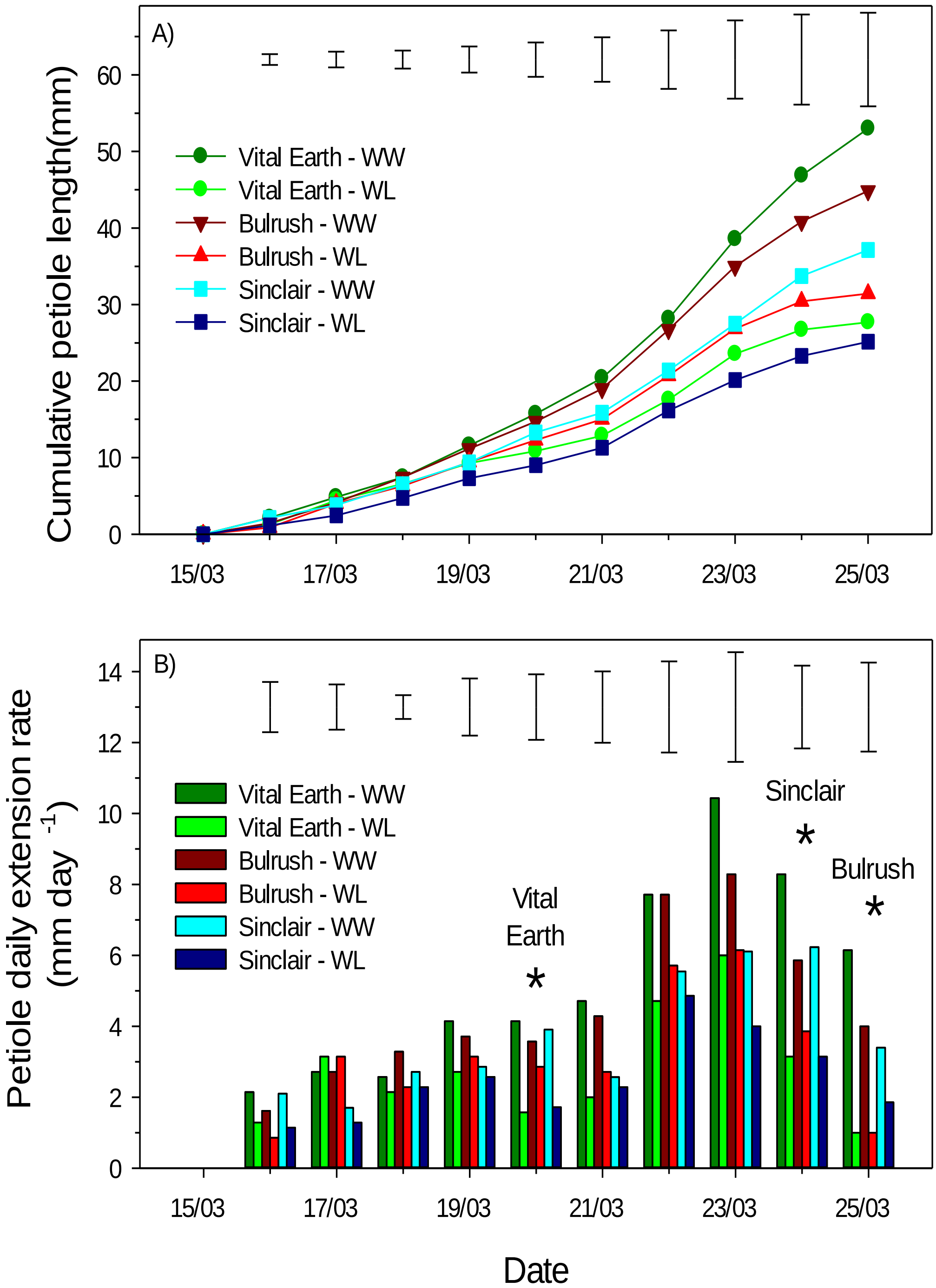

Figure 12. Changes in A) cumulative petiole growth and B) petiole extension rate of potted *Sidalcea* plants grown in peat-free (Vital Earth), reduced peat (Bulrush) and industry standard (Sinclair) substrates under well-watered or water-limited conditions. Asterisks indicate when physiological responses were first detected for all three substrates. Results are means of seven replicate plants; LSD values are for *P*≤0.05 with 30 degrees of freedom

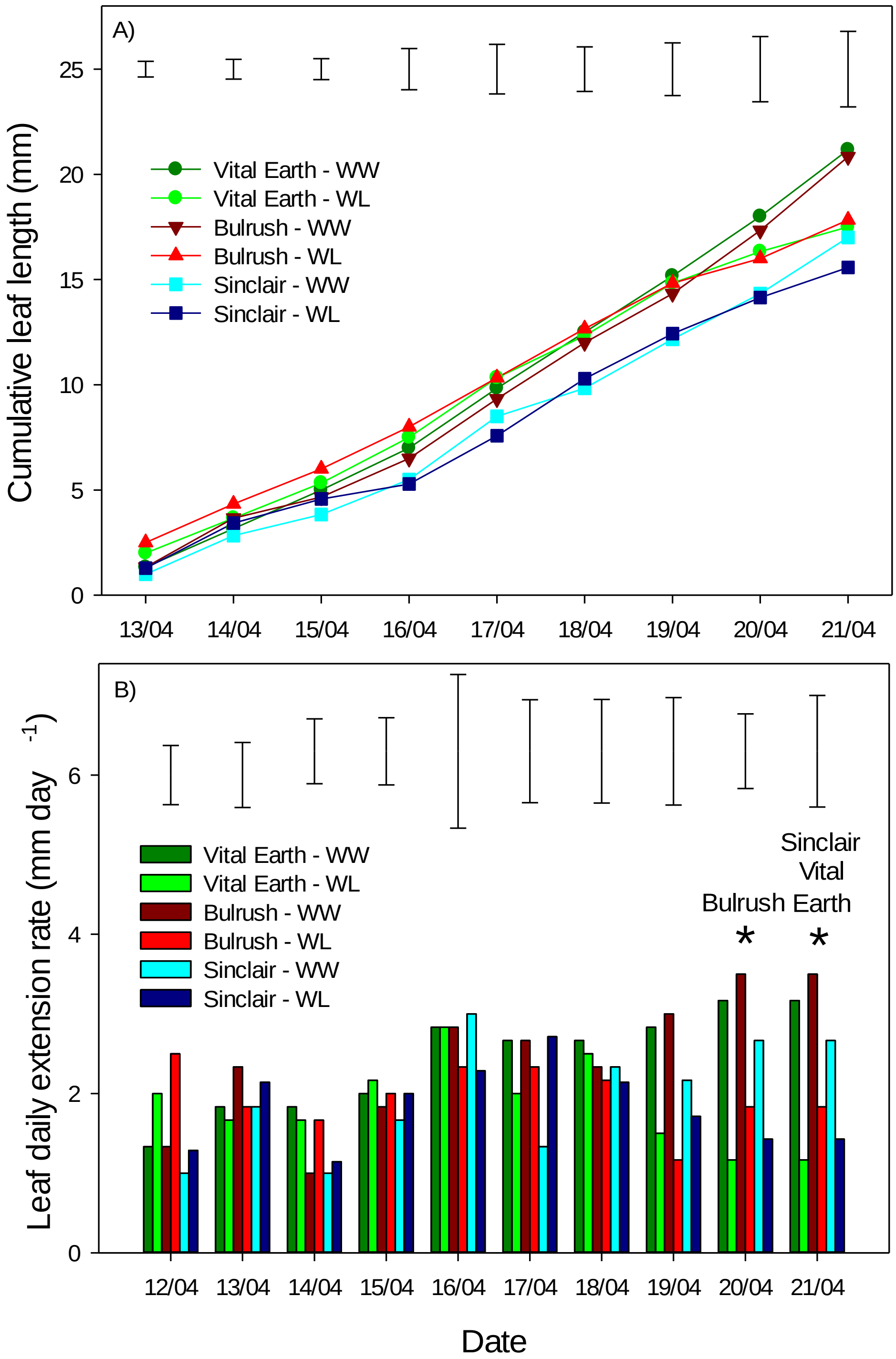

Figure 13. Changes in A) cumulative leaf growth and B) leaf extension rate of potted *Ribes* plants grown in peat-free (Vital Earth), reduced peat (Bulrush) and industry standard (Sinclair) substrates under well-watered or water-limited conditions. Asterisks indicate when physiological responses were first detected for all three substrates. Results are means of six replicate plants; LSD values are for $P \leq 0.05$ with 26 degrees of freedom

Defining the optimum range of VSMC

Plant-and-pot weights and VSMC at which physiological responses to drying soil were first detected were determined for each crop and substrate. The optimum range of substrate moisture content lies between the VSMC at this point and pot capacity (Tables GS1, GS3, GS5). For *Sidalcea* and *Escallonia*, since the first signs of wilting coincided with the onset of stomatal closure and lowered *E*, therefore it was thought prudent to raise the irrigation set points to ensure that plant quality would not be compromised. A 'low risk' strategy was therefore developed for all three crops to accommodate the inevitable logistical constraints to irrigation scheduling that occur during commercial production. Thus, the VSMC recorded 24 h before the initiation of the most sensitive physiological response was used as the lower irrigation set point (Table GS2).

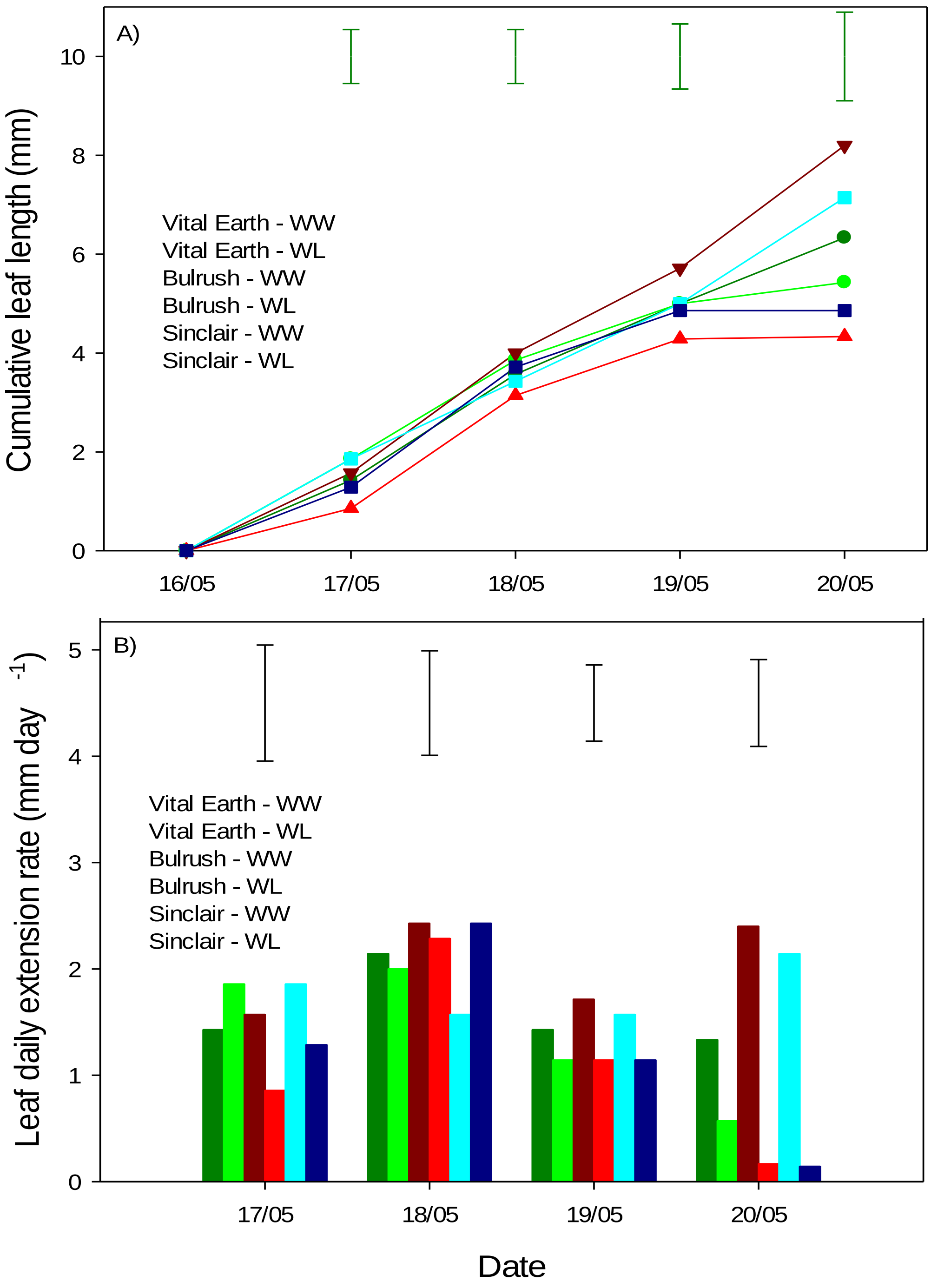

Figure 14. Changes in A) cumulative leaf growth and B) leaf extension rate of potted *Escallonia* plants grown in peat-free (Vital Earth), reduced peat (Bulrush) and industry standard (Sinclair) substrates under well-watered or water-limited conditions. Asterisks indicate when physiological responses were first detected for all three substrates. Results are means of seven replicate plants; LSD values are for *P*≤0.05 with 30 degrees of freedom

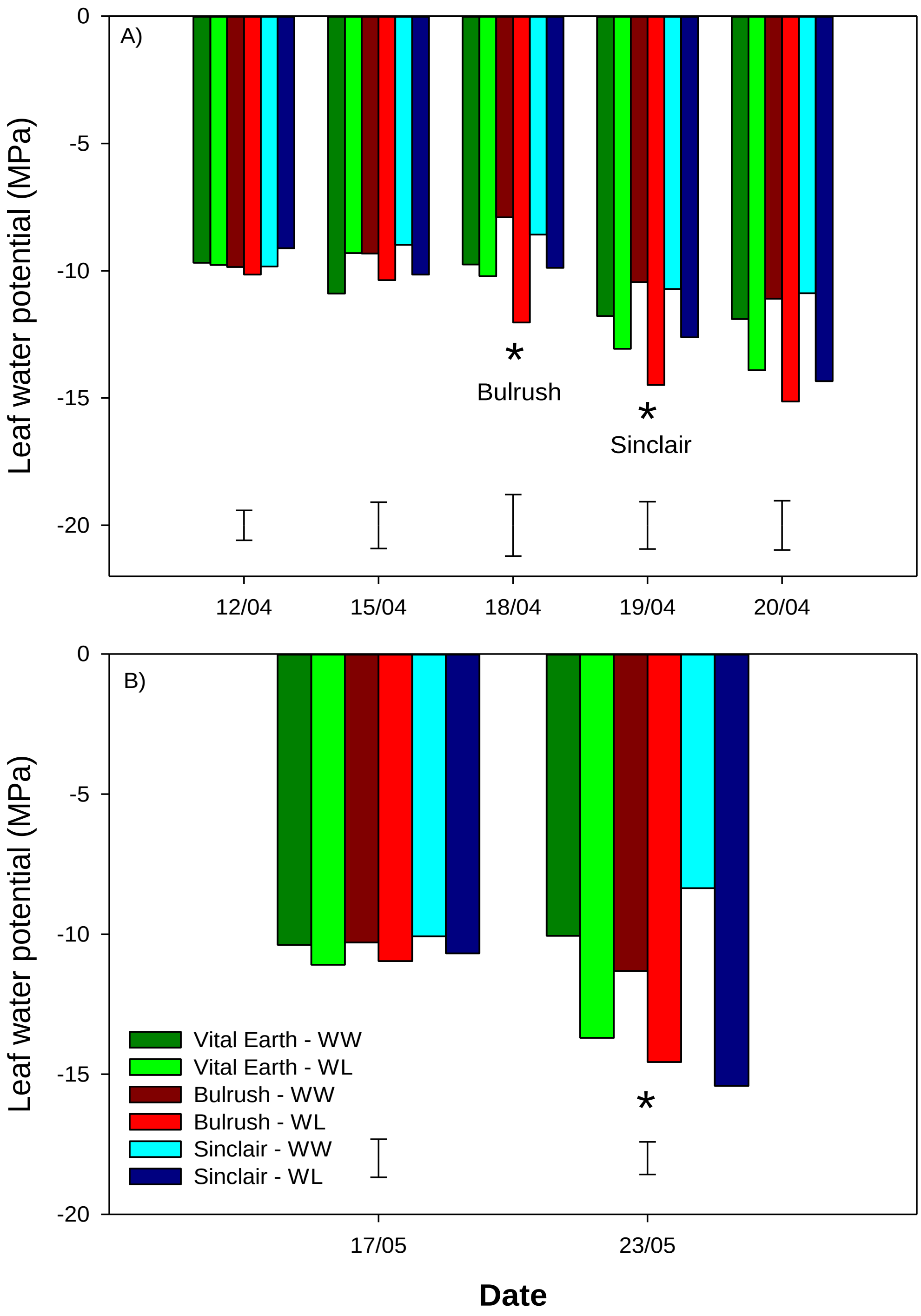

Figure 15. Changes in leaf water potential in A) potted *Ribes* plants and B) potted *Escallonia* plants grown in peat-free (Vital Earth), reduced peat (Bulrush) and industry-standard (Sinclair) substrates under well-watered or water-limited conditions. Asterisks indicate when physiological responses were first detected for all three substrates. Results are means of seven replicate plants; LSD values are for P≤0.05 with 30 degrees of freedom

Discussion

The main aim of the work in the project year one was to define the optimum range of VSMC for the peat-free, reduced peat and industry standard substrates. This was achieved by imposing gradual substrate drying and identifying the VSMC at which physiological responses were first triggered. For *Sidalcea* the VSMC at this point was lowest in the industry standard (Sinclair) substrate and highest in the reduced peat (Bulrush) substrate (Table GS2). For Ribes, the VSMC at the point at which physiological responses were first triggered was lowest for reduced peat (Bulrush) substrate and highest for peat-free (Vital Earth) substrate (Table GS4). *F*or *Escallonia,* the VSMC at this point was also lowest in reduced peat (Bulrush) substrate and highest for the industry standard (Sinclair) substrate (Table GS6). Differences in these values reflect differences in available substrate water in the three substrates, which is influenced by their composition (for example the proportion of peat); however the results obtained for *Ribes* and *Escallonia* indicate that these values are also crop-dependent.

Both *Sidalcea* and *Ribes* proved moderately tolerant of substrate drying; however by comparison *Escallonia* showed earlier physiological responses to substrate drying and was less able to adapt to the stress imposed by substrate drying. After only four days following reduced irrigation of *Escallonia,* significant differences between well-watered and water-limited plants were observed in all measured physiological responses (with the exception of petiole extension in plants growing in peat-free substrate), whereas significant differences in some physiological responses were first observed in *Sidalcea* and *Ribes* water limited plants growing in peat-free substrate five days and six days (respectively) following reduced irrigation. In order to elicit further physiological responses in *Sidalcea* and *Ribes* plants it was necessary after six days to decrease further the volume of water applied to the water limited plants.

The optimum ranges of VSMC will now be used in experiments on the EMWC to determine whether plant growth and quality in peat-free and reduced peat substrates are similar to those in industry standard substrate when irrigation scheduling is optimised. Drip irrigation will be controlled automatically using Delta-T SM200 soil moisture probes connected to GP1 data loggers to maintain the VSMC within the optimum ranges. Plant growth and development, production time to saleable product and overall plant quality at simulated dispatch date will be assessed in each of the three substrates. The volumes of irrigation water needed to maintain the substrates within their respective optimum ranges will also be measured to determine whether the use of reduced peat or peat-free substrates will reduce water use efficiencies during production.

Plants on the EMWC will be left to over-winter and measurements of pot weights and VSMC will be made each month to determine whether the more freely-draining reduced peat and peat-free substrates are less prone to waterlogging. Visual inspections of root and canopy health will be carried out in the following spring to determine whether plant vigour is improved in the more freely-draining substrates.

The approach used in this project to define the optimum range of VSMC has also provided information on the appropriate VSMC to use for Regulated Deficit Irrigation (RDI). Although not part of this project, the use of RDI with peat alternatives has the potential to reduce water inputs, control excessive vigour without reliance on plant growth regulators and improve tolerance to stresses encountered during distribution and retailing.

The development of new guidelines to optimise irrigation scheduling for peat-free, reduced peat and industry standard substrates will also help to reduce losses associated with over-watering of peat alternatives. Unlike the obvious wilting response to limited substrate water availability, the effects of over-wet substrates on plant growth and development can be more subtle and may go unrecognised but root and shoot growth, resistance to pests and diseases, resilience to high evaporative demands and overall plant quality can all be reduced in the long term. The identification of VSMC at which hypoxic (low oxygen) and anoxic (no oxygen) conditions develop in the substrate would help to reduce wastage during production associated with over-watering.

Conclusions

- Plant-and-pot weights and VSMC were highest at pot capacity in the Industry standard (Sinclair) substrate, which contains the highest proportion of peat
- VSMC values at which plant physiological responses are triggered were identified for *Sidalcea, Ribes* and *Escallonia* grown in industry standard (Sinclair), reduced peat (Bulrush) and peat-free (Vital Earth) substrates
- The VSMC at which physiological responses to drying substrate varies according to crop and substrate
- The optimum range of VSMC and plant-and-pot weights in each substrate were determined for *Sidalcea, Ribes* and *Escallonia*

- These values will be used in experiments on the EMWC in 2011 to develop irrigation schedules for each substrate that match supply with crop water demand

Knowledge Exchange and Technology Transfer

An article summarising the project aims and objectives and results to date will be published in the May 2012 edition of HDC News.

Meeting and demonstrations

- Meetings with the project steering group were held on 30 November 2010 and 16 March 2011 to discuss approaches and finalise experimental plans, discuss results, view on-going trials and plan knowledge exchange and technology transfer events
- The project aims and objectives were discussed with Dr Paul Alexander during a visit by EMR project staff to RHS Wisley to view on-going peat alternative trials
- The methodologies used to determine the optimum range of moisture contents were discussed with Dr Paul Alexander and Nick Morgan (RHS Wisley) during a visit on 2 March 2011 to view the trials at EMR

Visits to Grower sites

Managing production using peat alternatives was a key topic covered in discussions with the following growers: Jim Willis (Binsted Nursery); Karl O'Neill and Geoff Caesar (Bransford Webbs); Alastair Hazell (Darby Nursery Stock Ltd); Fizz Newington (Dingley Dell Nurseries); Nick Dunn (Frank P Matthews Ltd); Paul Dyer (Hedgehog Plants); Paul Howling (Howard Nurseries); John Hall (John Hall Plants); John Richards (John Richards Nurseries); Malcolm Dick (John Woods Nurseries); Charles Carr and Ian Ashton (Lowaters Nursery); Robert Small (North Hill Nurseries); Toby Marchant (Orchard Dene Nurseries); Lee Woodcock (Palmstead Nurseries); Peter Blakey (Plants Ltd); Bill Godfrey (W Godfrey & Sons Ltd); David Hide and Tim Lawrence-Owen (Walberton Nursery); Paul Wharton and Robert Wharton (Whartons Nurseries).

Acknowledgements

We thank Mr Roger Payne for excellent technical assistance, and also Mrs Dilly Rogers, Mr Paul Bridger and Mr Gary Saunders for their support. We also thank Bulrush Horticulture Ltd, William Sinclair Horticulture Ltd. and Vital Earth Ltd for their 'in-kind' contribution of the substrates, and Susan Holmes (Susie Holmes Consulting Ltd) for her expert advice on growing media. Not least we thank Project Co-ordinators Mr John Adlam, Mr Malcolm Dick, Dr Bill Godfrey, and Mr Alastair Hazell for their invaluable input.

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APPENDIX I

Table A1. Comparison of substrate analysis results: pH, Density, Dry Matter, Dry Density, Ca, chloride, Mg, P, K, ,Na, N, EC and trace elements

Analyte	Extraction with CAT solution	Extraction with water		
	Vital Earth Peat-free	Vital Earth Peat-free	Bulrush 50% peat	Sinclair 75% peat
pH	7.40	7.37	5.39	5.70
Density kg m^{-3}	518	518	367	481
Dry Matter %	40.4	40.4	39.2	33.7
Dry Density kg m^{-3}	209.3	209.3	143.9	162.1
Calcium mg L^{-1}	-	6.5	35.5	74.2
Chloride mg L^{-1}	-	223.4	18.4	12.2
Magnesium mg L-1	137	1.9	50.0	59.8
Phosphorus mg L^{-1}	40.5	17.4	56.0	29.7
Potassium mg L^{-1}	560	188.4	194.8	166.9
Sodium mg L^{-1}	104	49.6	36.5	31.5
Ammonia-N mg L^{-1}	323.0	127.6	35.3	100.6
Nitrate-N mg L^{-1}	< 0.5	< 0.6	94.5	190.2
Total Soluble N mg L^{-1}	323.0	127.6	129.8	290.8
Conductivity µS cm^{-1}	319	315	266	377
Sulphate mg L^{-1}	43.7	128.1	205.7	218.4
Boron mg L^{-1}	0.56	0.23	0.17	0.15
Copper mg L^{-1}	0.47	0.08	0.07	< 0.06
Manganese mg L^{-1}	62.10	0.25	0.59	0.87
Zinc mg L^{-1}	9.16	0.16	0.22	0.11
Iron mg L^{-1}	43.8	3.54	1.00	0.92
Molybdenum mg L^{-1}	< 0.5	-	-	-

Table A2. Air-filled porosity and particle size analysis for the three substrates used in the experiments

Parameter	Substrate		
	Vital Earth peat-free	Bulrush 50% peat	Sinclair 75% peat
Air Filled Porosity fresh basis %	32.5	19.7	11.8
Passing 1 mm % w/w	17.2	31.3	26.4
Retained at 1 mm % w/w	22.5	13.2	12.8
Retained at 2 mm % w/w	33.0	13.4	17.1
Retained at 4 mm% w/w	23.1	23.6	27.5
Retained at 8 mm % w/w	4.2	15.4	16.3
Retained at 16 m % w/w	0	3.0	<0.1
Retained at 31.5 mm % w/w	0	<0.1	<0.1

Table A3. Comparison of pH, EC and Nitrogen (extractable in water) in peat-free substrate (Vital Earth), repeat extractions.

Analyte	Date of analysis		
	December* 2010	January 2011	February 2011
pH	7.8	7.7	7.37
Conductivity uS cm^{-1}	269	294	315
Ammonia-N mg L^{-1}	1	88	127.6
Nitrate-N mg L^{-1}	6	9	<0.6
Total Soluble N mg L^{-1}	7	97	127.6

*Analyses in December and January were performed for Vital Earth by Alliance Technical Laboratories Ltd, Ipswich, Suffolk. Analysis in February was performed for EMR by NRM Ltd, Bracknell, Berkshire