Knowledge and tools to manage fertigation technologies in highly productive citrus orchards for minimal environmental footprint

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Part 1 - Summary details

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Part 3 – Executive summary

Drip irrigation/fertigation (“advanced fertigation”, “open hydroponics”) is being adopted by the Australian citrus industry. Hardware sophistication and the complexity of management regimes being used vary enormously; from old paradigms applied using modern equipment, through to approaches used overseas, but untested under Australian conditions. Generally, these technologies are being adopted without support. This project aimed to address knowledge gaps and test assumptions regarding the application of modern approaches to the delivery of water and dissolved mineral fertilisers to citrus trees under Australian conditions.

Seedling rootstocks growing in sand culture were used to investigate the impact of variations in nutrient solution composition. Relative vigour of the rootstocks was maintained irrespective of nutritional treatment. The rootstock genotypes differed in their rate of response to increasing N supply and the efficiency with which N was used in the shoots. The most vigorous rootstock responded to small increments in N supply and achieved maximum growth with lower tissue N than less vigorous rootstocks. Across all rootstocks, more than 45 mg N/L in the nutrient solution conferred no additional advantage. Further, optimum potassium concentration appeared to be around 23 mg/L. Neither shoot biomass production nor macronutrient accumulation were advantaged by acidification of the nutrient solution.

Some aspects of modern irrigation/fertigation practices were compared using young navel oranges at Dareton. Similar amounts of water and fertiliser were supplied in either a “best practice” approach or an “open hydroponics” approach. The strongest influence on tree behaviour was season. Neither irrigation nor fertiliser management influenced tree behaviour to any great extent. The composition of soil solutions was extremely variable. Despite best practice ET_o scheduling, high concentrations of N in the irrigation water resulted in a gradual movement of NO_3^- down the soil profile. In a fertigation program based on reduced and oxidised forms of N, nitrate-N greater than ~34-45 mg/L was clearly in excess of the roots’ ability to take up NO_3^-.

Water and solute movement in lysimeters was quantified and compared to field measurements. Various scenarios were explored using a 2D/3D water and solute movement model (“Hydrus”) that evaluated NO_3^- movement under different fertigation application patterns, involving pulsed and non-pulsed irrigation, and variable timing of fertigation applications across the daily irrigation pattern. The simulations suggested that injection of NO_3^- into the irrigation water in the early or middle pulses of daily irrigation resulted in less NO_3^- being retained in the rootzone for uptake by tree roots, and concomitant greater leaching losses than application of fertigation in the later part of irrigation pulses, or at a low level across the whole day.

The application of modern fertigation strategies is unsupported by objective public-domain data, and the long term impact of such strategies under Australian conditions is unknown. A field site was established to quantify the long term responses of three selections of navel oranges on five different rootstocks to fertiliser delivered using modern delivery technology. The site will serve as a research and technology transfer resource well into the future, and is probably unique in the world. Industry support in the future will be needed to take full advantage of the potential benefits of this site.

Two Excel spreadsheet-based decision support tools were developed to assist irrigators to make more informed decisions regarding irrigation scheduling and fertilisers use. One of these, E-Schedule, an irrigation scheduling decision support tool, was developed to make it simpler to bring together all the disparate pieces of information, including weather predictions, needed to make informed irrigation scheduling decisions. E-Schedule has nationwide applicability.

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Background

It is generally accepted that drip irrigation is currently the most efficient means of supplying water to the roots of permanent tree crops such as citrus. The adoption of drip irrigation systems more recently has been accompanied by the adoption of technologies that allow dissolved mineral nutrients to be injected into the irrigation water. The term "fertigation" is used to describe the supply of soluble mineral fertilisers in the irrigation water.

The degree of sophistication of the injection technologies being used and the complexity of management regimes being applied vary enormously. For example, some systems are used to only supply a limited range of mineral nutrients, principally nitrogen (N), phosphorus (P) and potassium (K), on a few occasions per year. Essentially, these systems are simply replacing surface application of solid fertilisers. At the other extreme, some systems are being used to supply all the trees' mineral nutrient needs continually throughout the growing season, and the soil essentially acts as a physical support for the tree roots and to store water and nutrients; an approach referred to as "open hydroponics". These more complex technologies are sometimes adopted within a confidential service agreement, in which management regimes (*i.e.* fertiliser "recipes") are not in the public domain. More often, fertigation technologies are being adopted without support, mineral nutrient supply regimes are based on experience and hearsay, and inputs often reflect the inefficiencies inherent in delivery technologies used in the past. Nonetheless, the citrus industry's experience is generally positive; albeit with the proviso that possibly the basis of any comparisons may be poor.

Australian horticultural industries are major users of both drip irrigation and fertigation technologies. For example, about 4,000 ha of citrus and almonds in the Riverland, Sunraysia and Riverina regions are managed using open hydroponic approaches. These approaches are based on high frequency (daily) irrigation cycles coupled with as-frequent delivery of soluble mineral nutrients to roots. Objective scientific evidence supporting frequent applications of water and nutrients versus more traditional management is lacking. Rigorous objective scientific scrutiny in the public domain is, therefore, not possible, and the limited scientific literature is ambivalent (Bar-Yosef, 1999; Sorgona *et al.*, 2006). These criticisms highlight the need for adopters of the technology to have available, at the very least, qualitative information regarding the effects of alternative irrigation strategies and the ability of roots to take up nutrients from the root zone. Advances in the public domain in this area are also limited by a lack of purpose-established trial sites.

The potential for movement of mineral nutrients—such as nitrogen (as nitrate)—below the root zone and into ground and surface waters using these approaches is high. This is due to a number of factors; the amounts being supplied, the ability of roots to take up those nutrients and the ability of irrigators to manage drainage and hence leaching. Irrigated horticulture has, in general, been identified as the major source of nitrogen in drainage water in the Murray Darling Basin (Harrison, 1994). Supporting this contention, escape of water and NO_3^--N during the growing season below the rootzone as high as 34 mm and 10 kg ha^{-1}, respectively, in a single month, have been measured in a citrus orchard in south west NSW[1].

The citrus industry is a mature industry in comparison to the olive and almond industries despite being roughly comparable with respect to areas under trees. There are many small scale owner-operator citrus producing enterprises in comparison to a few large almond and olive producing enterprises employing professional managers. About 75% of the Australian citrus industry is located in the Murray-Darling Basin, utilising the lighter-textured free-draining soils adjacent to the Murray, Darling and Murrumbidgee Rivers, and so potential off-site effects of these types of approaches may have wider implications. Thus there is a strong

[1] Biswas, T. 2008. Personal communication

case to demonstrate to citrus producers the integration of modern efficient drip irrigation management with current "best bet" nutrient supply based on knowledge of citrus nutrient needs. There is also a strong need to widen the knowledge and skills base of citrus producers and increase the availability of decision support tools.

Objectives

Develop guidelines, practical grower-friendly tools and information packages, provide training for irrigators and support industry for the sustainable and economical use of the new fertigation technologies in citrus production by…

- quantifying nutrient capture by roots of commercially relevant citrus rootstock genotypes in relation to supply,
- establishing a statistically rigorous commercial-scale experimental site featuring commercially relevant citrus scion varieties growing on commercially relevant rootstock genotypes to enable short- and long-term responses to nutrient supply to be quantified,
- studying the effect of commonly practiced high intensity fertigation regimes on salt, water and nutrient movement within and below the root zone,
- developing a framework to quantify water and nutrient escape below the rootzone of citrus trees growing in lysimeters,
- calibrating a 2D/3D solute transport model under lysimeters and validating under field conditions for predicting nutrient and water flux beyond the root zone,
- developing tools for irrigators to use water and nutrients more efficiently,
- communicating to industry the knowledge needed to use water and nutrients more efficiently.

Thus, the project had a number of components to address the objectives set out above, and each of these will be described separately.

Efficient nutrient management

Nutrient capture by roots of commercially relevant citrus rootstocks

Summary

Rootstock-specific fertiliser programs are not generally considered by Australian citrus producers despite the many reports describing the impact of rootstock genotype on scion nutrient status. This "one size fits all" approach, combined with the adoption of technologies allowing greater control over the supply of dissolved mineral fertilisers to tree roots and the adoption new rootstocks, necessitated investigating the response of the rootstocks being used, and being increasingly adopted, to nutrient supply. Thus, a series of experiments were conducted on seedling rootstocks growing in sand culture to investigate the impact of important fertigation program variables on growth and N, P and K uptake and transport by different rootstocks. Further, because citrus are not grown on their own roots, and roots and shoots communicate with each other, an additional experiment needed to be at least set up to investigate the ability of roots to influence scion behaviour and *vice versa*. An additional facet of this part of the project was to use the plant material generated by these experiments to determine the feasibility of using a hand-held instrument to estimate leaf N status as a prelude to developing this technology as a decision support tool for citrus producers.

Irrespective of whatever nutritional treatment was applied (N, K, Si or nutrient solution pH), the relative vigour of the rootstocks was maintained. Nitrogen supply strongly affected shoot biomass production, and the rootstocks differed in the rate of response to increasing N supply and the efficiency with which N was used in the shoots. The most vigorous rootstock responded to small increments in N supply and achieved maximum growth with lower tissue N than less vigorous rootstocks. Across all rootstocks there appeared to be little advantage supplying nutrient solution with N present at concentrations greater than 45 mg/L.

Grown with non-limiting N supply, all rootstocks behave similarly to increasing K supply, and demonstrated optimum shoot biomass production was achieved when the K concentration in the nutrient solution was around 23 mg/L. Growth was limited by K supply below this concentration and probably by reduced uptake of other important cations above this concentration.

Acidifying the nutrient solution, a key part of the open hydroponics approach to supplying water and fertiliser to trees, did not improve shoot biomass production or result in greater accumulation of the major macronutrients in the shoots of any rootstock growing in sand culture.

Good correlations were obtained between the absorbance of UV light by leaves and shoot %N, or the shoot C:N, or the concentration of N in the nutrient solution. These relationships suggest that such a measurement may be a means of assessing the N status of trees non-destructively and in real time. Further work is required to flesh out the relationship, and establish a suitable measurement protocol that addresses confounding issues such as leaf age.

Introduction

Rootstocks are used by citrus producers for a variety of reasons, but principally for tolerance of soil-borne diseases, scion vigour and longevity, and fruit quality. Because citrus is salt sensitive, ability to exclude salt from the scion is also a desirable feature, and a tolerance of high pH soils is important in those regions with calcareous soil types. Some older orange orchards still have trees on rough lemon (*Citrus jambhiri* Lush.) and sweet orange (*Citrus sinensis* [L.] Osbeck), but more recent plantings are predominantly on trifoliate orange

(*Poncirus trifoliata* [L.] Raf.), Troyer or Carrizo citrange (both *C. sinensis* × *Poncirus trifoliata*), but, Swingle citrumelo (*C. paradisi* Macf. 'Duncan' grapefruit × *P. trifoliata* [L.] Raf.), macrophylla (*C. macrophylla* Webster) and volkameriana (*C. volkameriana* Ten. & Pasq.) are also being used. The latter rootstocks are more commonly used in overseas citrus producing regions than they are in Australia.

Despite the wealth of field observations that attest to the impact of rootstock on scion mineral nutrient levels (Wutscher and Olson, 1970; Taylor and Dimsey, 1993), rootstock is not regarded as an important consideration in managing citrus mineral nutrition by industry. Further, fertiliser response functions developed for citrus stemmed from trials involving, at best, trees on two rootstocks (*e.g.* Sarooshi *et al.*, 1991), but usually a single rootstock (*e.g.* Bouma, 1959), and are based on outdated delivery methods and strategies (*i.e.* surface application once or twice per season) (*e.g.* Sarooshi *et al.*, 1991). As mentioned previously, technologies to deliver dissolved mineral fertilisers in the irrigation water are readily available, and at first glance there is a *prima facie* case that use of these technologies should be associated with more efficient use of fertiliser. Citrus producers do not have the knowledge available to gain the most from their investment in these technologies. The need for more rootstock-related fertiliser use recommendations has been recognised to some extent overseas (*e.g.* Mattos *et al.*, 2006). Silicon was also included as an experimental variable because of the growing appreciation of its role in plant physiology and stress responses (Richmond and Sussman, 2003; Raven, 2003).

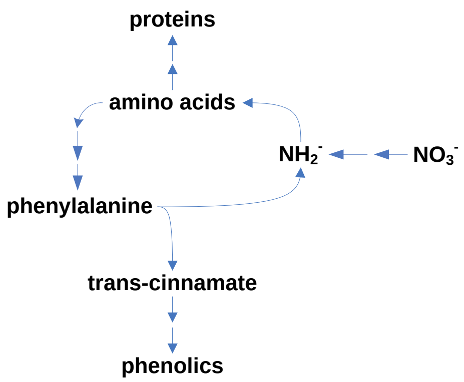
Acidification of the irrigation water/dissolved mineral nutrient mix is a key part of the "open hydroponics" approach to supplying water and mineral nutrients to citrus roots. Plants can be loosely classified into two classes depending on their preference for high pH/calcareous soils or acid soils; these classes of plants are known as calcicole and calcifuge (Marschner, 1986). One justification for acidification of fertigation solutions may be an assumption that citrus genotypes used as rootstocks have a preference for acid soils. However, the range of citrus rootstocks being used in Australia encompasses both calcicole and calcifuge genotypes (Treeby and Uren, 1993). Another rationale for the acidification of the irrigation water/dissolved mineral fertiliser solution may lie in the relationship between xylem fluid pH and stomatal activity (Wilkinson and Davies, 1997); stomatal aperture is reduced when apoplastic pH is above 7 (Forner-Giner *et al.*, 2011). Irrigation water/dissolved mineral fertiliser solution of pH 6.3 may maintain xylem fluid pH at about 6.3, keeping stomates open and forcing transport of mineral nutrients to leaves and photosynthesis by the leaves. Thus, it is important to determine whether acidification of the irrigation water confers any advantage in terms of nutrient uptake by any of the rootstocks being used, or likely to be adopted, by Australian citrus producers.

An additional layer of complexity is the interaction between rootstock and scion. Root to shoot and shoot to root signalling are well documented phenomena (Forde, 2002; Schachtman and Goodger, 2008). An obvious manifestation of these phenomena is the effect of different citrus rootstocks on scion leaf water potential (Albrigo, 1977). There is a growing appreciation that the xylem is not just a "pipe" conveying water and nutrients from the roots to the shoots and that the ion composition of the xylem fluid can interact with structural polysaccharides to affect hydraulic conductivity (Nardini *et al.*, 2011). The only measurement of the extent of any such effect in citrus suggests ion-mediated changes on the hydraulic conductance of sour orange (*C. aurantium* L.) to be around 28% (Jansen *et al.*, 2011). The complexity arises because citrus trees (as scions) are frequently growing on the roots of another citrus species, or a species from another closely related genus, or a multi-species hybrid. This means that parts of the xylem are from different species, and the extent of ion-mediated effects on hydraulic conductivity may be different. One approach to investigating the complex interaction between rootstock and scion is to use reciprocal grafts; that is, a scion variety grafted onto the same variety and onto a rootstock, and a rootstock variety grafted onto a scion variety and onto the same rootstock. Ideally, this type of work needs be based on clonal (*i.e.* vegetatively propagated) material to remove another source of error; namely, seed to seed variability. This type of approach should shed some light on the influence the rootstock has on the scion physiology and *vice versa*. The relatively slow growth rate of citrus and the desirability of using vegetatively propagated material means that progress in this area is not likely in the short term. It is probably for this reason that only a single scientific paper (Bleda *et al.*, 2011) could be found that employed this technique to study citrus scion/rootstock interactions.

In addition, managing tree nutrient status is made more difficult by an inability to assess tree nutrient status in real time. This has become more relevant with the advent and adoption of technologies to alter an orchard's mineral nutrition program at very short notice. Evaluation of phenols may provide a pathway for more immediate evaluation of tree nutrient status. Phenols are a class of compounds found in plants. Phenols absorb UV light, and their production is favoured when tissue N levels limit growth (Cartelat *et al.*, 2005). This phenomenon is known as the "protein competition model" (Jones and Hartley, 1999), the essence of which is summarised schematically in **Figure 1**, and this relationship was the basis for the development of instrumentation to measure the absorbance of UV light by leaf epidermal cells (Goulas *et al.*, 2004). Research has focussed on calibration using field crops such as wheat (Cerovic *et al.*, 2002; Meyer *et al.*, 2006). Its potential use in woody perennial crops has not been investigated.

Figure 1 Diagrammatic summary of the protein competition model

Amino acid production relies on a steady supply of NH_2^-, either produced from recently taken up NO_3^- or the re-cycling of NH_2^- in phenylalanine, one of the amino acids. What is left of the phenylalanine molecule after the removal of the NH_2^- group is directed into the production of phenolic compounds. Recycling occurs to some extent all the time, but occurs at a higher rate when NO_3^- is in short supply, and at a lower rate when ample supplies of NO_3^- are available (Jones and Hartley, 1999).



Materials and methods

Rootstock genotypes were selected for study on the basis of current plantings and likely future plantings inferred from commercial orders for rootstock seeds and the outcomes of current rootstock evaluation trials at Dareton. Seeds were extracted from mature Symons sweet orange (*Citrus sinensis* [L.] Osbeck), trifoliate orange (*Poncirus trifoliata* [L.] Raf.), Troyer citrange (both *C. sinensis* × *P. trifoliata*), Swingle citrumelo (*C. paradisi* Macf. "Duncan' grapefruit × *P. trifoliata* [L.] Raf.), macrophylla (*C. macrophylla* Webster) and volkameriana (*C. volkameriana* Ten. & Pasq.) fruit collected from source trees established on Dareton Primary Industries Institute. The seeds were rinsed clean of fruit flesh in tap water, sterilised at 40°C in water for 10 minutes, dried at room temperature, dusted in Thiram and stored at 4°C in the dark until needed. Depending on availability most seed used in the experiments described below was less than 12 months old.

Seeds were germinated by sowing at a depth of 10 mm in pots containing washed coarse river sand or vermiculite, and the pots placed on a heat bed in a glasshouse. Germination rates were generally between 50 and 90%, but some batches of seeds failed to germinate. Generally, seedlings were suitable for transplanting 3 months after sowing.

Steam-sterilised (65^{o}C for 2 hours) coarse river sand was used in all experiments.

The seedlings were rinsed clean of the germination medium and planted in steam sterilised sand in 150 mm diameter black plastic pots. The pots were placed on benches in a glasshouse. Each bench allowed for 84 pots in 14 rows of 6. Each pot was irrigated by a single micro-jet sprinkler with 8 outlets.

Seven pairs of 220 L tanks supplied 7 nutrient supply treatments via a reticulation system to each bench, and nutrient supply treatments were applied to whole rows.

There were 5 benches, and each bench was split into 2 "plots" of 7 rows.

Depending on the size of the plants, the pots were irrigated 2-4 times per week, and on each occasion sufficient nutrient solution was applied to flush out any nutrient solution remaining in the pot from the previous irrigation.

A modified Hoagland's solution (Hoagland and Arnon, 1938) was used throughout. The sources of the mineral nutrients are listed in **Table 1**. Mineral elements not previously considered essential plant nutrients, but now considered at least beneficial if not essential, were also added. The concentrations of each mineral nutrient in the final nutrient solution are presented in **Table 2**.

The nutrient solutions were made up using reverse osmosis water with an electrical conductivity of 0.5 μSiemens m^{-1}. The nutrient solutions were thoroughly mixed by circulating the solutions from the bottom to the top using 30L min^{-1} pumps, which also served to pump the nutrient solutions to the pots. The pH of this nutrient solution was around 6.2.

Table 1 Sources of mineral nutrients used in modified Hoagland's solution

Nutrient salt, acid or chelate	Alternate names	Empirical or structural formulae
ammonium nitrate	nitram	NH_4NO_3
potassium orthophosphate	potassium di-hydrogen phosphate	KH_2PO_4
potassium sulphate		K_2SO_4
calcium nitrate tetrahydrate		$Ca(NO_3)_2.4H_2O$
magnesium sulphate heptahydrate	Epsom salts	$MgSO_4.7H_2O$
orthoboric acid	boric acid, boracic acid	H_3BO_3
manganese dichloride tetrahydrate		$MnCl_2.4H_2O$
zinc sulphate heptahydrate		$ZnSO_4.7H_2O$
copper sulphate		CuSO4
sodium molybdite		$Na_2MoO_4.2H_2O$
ferric ethylenediamine-N,N'-bis(2-hydroxy)phenylacetic acid	Sequestrene 138, FeEDDHA	$FeC_{18}O_6N_2H_{16}$
disodium silicate pentahydrate		$Na_2SiO_3.5H_2O$
cobalt dinitrate hexahydrate		$Co(NO_3)_2.6H_2O$

The concentrations of specific nutrients were varied for a series of experiments aimed at testing an underlying paradigm that underpins open hydroponics as practiced in the citrus industry, namely, that the roots of all rootstocks behave similarly in relation to nutrient solution supplied to the roots.

Table 2 Elements, forms and concentrations supplied in modified Hoagland solution					
	Element	**Symbol**	**Ions**	**Concentration**	
				mM	***mg L^{-1}***
Macronutrients	nitrogen	N	NO_3^- & NH_4^+	1.2	17
	phosphorus	P	PO_4^{3-}	0.4	12
	potassium	K	K^+	0.8	31
	calcium	Ca	Ca^{2+}	3.0	120
	magnesium	Mg	Mg^{2+}	0.5	12
	sulphur	S	SO_4^{2-}	1.3	42
	chloride	Cl	Cl^-	6	213
	sodium	Na	Na^+	4	92
	silicon	Si	SiO_3^{2-}	2	56
				µM	***µg L^{-1}***
Micronutrients	iron	Fe	Fe^{3+}	5	279
	boron	B	BO_3^{3-}	5	54
	manganese	Mn	Mn^{2+}	1	55
	zinc	Zn	Zn^{2+}	0.1	6.5
	copper	Cu	Cu^{2+}	0.1	6.4
	molybdenum	Mo	MoO_4^{3-}	0.5	48
	cobalt	Co	Co^{4-}	0.02	1.2

Nitrogen supply

Using ammonium nitrate (NH_4NO_3) as the N source, 7 N supply treatments were imposed on 6 rootstock genotypes. The lowest concentration supplied was 0.2 mM, and the concentration doubled with each increment up to 12.8 mM (**Table 3**); equivalent to approximately 16 to 1025 mg ammonium nitrate L^{-1}.

Table 3 Concentrations of ammonium nitrate (NH_4NO_3) supplied to seedlings of 6 citrus rootstock genotypes growing in sand culture

mM	mg L^{-1}
0.2	16
0.4	32
0.8	64
1.6	128
3.2	256
6.4	513
12.8	1025

The plants were maintained in sand culture for 4 months. Height was monitored fortnightly, and leaf phenolics in the youngest fully expanded leaf were measured monthly. At harvest, entire shoots were collected, rinsed in clean water and dried at 60°C for 7 days and the dry matter per plant was then determined. The dried shoots were ground to a fine powder and sent to NSW DPI's Wollongbar laboratory[2] for analysis. Tissue N and C levels were determined by thermal conductivity of the combustion gases following high temperature combustion in oxygen, and tissue nitrate levels determined spectrophotometrically on an aqueous extract prepared from the dry plant material.

Potassium supply

Seeds were germinated as in **Table 2**, and transplanted into sand after attaining a suitable size.

[2] NATA-accredited

The nutrient solutions supplied were as above, except that one third of the pots received K (as potassium sulphate) at 0.4 mM, one third received 0.8 mM and the remainder received 1.6 mM. The pots were irrigated 2 or 3 times per week, depending on weather conditions and the size of the plants. Harvesting and shoot biomass determinations were carried out as above. In addition to N and C determinations (as above), subsamples of the dried ground shoot material were also digested in boiling concentrated HNO_3 and the levels of P, K, Ca, Mg, S, Na, Al, B, Cu, Fe, Mn in appropriately diluted subsamples were determined against suitable standards in an inductively-coupled plasma emission spectrometer.

Solution pH

Seeds were germinated as above, and transplanted into sand after attaining a suitable size.

The pH of the nutrient solutions were adjusted to 6.3 or 7.7 with 1 N HCl or 1 N NaOH, as appropriate. The pots were irrigated 2 or 3 times per week, depending on weather conditions and the leaf area the plants were carrying. Harvesting and analytical procedures were as described for the potassium supply experiment above.

Silicon supply

Seeds were germinated as above, and transplanted into sand after attaining a suitable size.

The nutrient solutions supplied were as above, pH 6.3, but half the pots received no silicon and the other half received 2 mM Si (as disodium silicate pentahydrate). Harvesting and analytical procedures were as described for the potassium supply experiment above.

Leaf phenolics

All the experiments described above were used as sources of leaf material of differing mineral nutrition background. Measurements were conducted on the fully expanded leaves of seedling rootstocks throughout each experiment, but only the sets of measurements that were collected on the day that each experiment was harvested was used for analysis because these measurements could be directly related to the shoots' C:N ratio on that day.

A Dualex (Force-A, Orsay Cedex, France) is a hand held instrument that clips onto leaves (**Figure 2**) and non-destructively measures chlorophyll and phenolics using diodes emitting in the UV range and a non-absorbing reference wavelength in the visible range. The impact of the various treatments applied throughout (*i.e.* rootstock, N supply, K supply, Si supply and solution pH) on the measure, and the relationship between the C:N ratio of the rootstock seedling shoots on the day of harvest and the Dualex measurement collected on that day was explored using regression analysis.

Figure 2 Hand held Dualex instrument for measuring leaf chlorophyll and phenolics

Reciprocal grafting

Cuttings of the scion varieties Valencia (*Citrus sinensis* [L.] Osbeck), Washington navel, (*C. sinensis*), Imperial mandarin (*C. reticulata* [L.]), Eureka lemon (*C. limon* Burm. f.) and Marsh grapefruit (*C. paradisi* Macf.) and the rootstock types, volkameriana (*C. volkameriana* Ten. & Pasq.), rough lemon (*C. jambhiri*), sweet orange (*C. sinensis*), sour orange (*C. aurantium* L.) , Carrizo citrange (*C. sinensis* × *P. trifoliata*) and trifoliate orange (*P. trifoliate*) were collected from source trees growing on Dareton Primary Industries Institute and Loxton Research Centre in December 2008.

Single node cuttings, with leaves cut in two and an angled cut at the basal end, were dipped in a commercial gel formulation of indole butyric acid (3 g L^{-1}) to promote formation of callus tissue and roots. The dipped ends were then inserted into moist mix of 1:1 river sand and perlite in boxes to a depth of 100 mm, and the boxes were placed on a heated mist bed. The cuttings remained on the mist bed for 6 months, after which cuttings that had developed roots and shoots ("rootlings") were potted up into larger pots in potting mix and grown on in a poly-house for a further 18 months. The rootlings were trimmed to single stems and watered and fertilised regularly to promote growth. Generally, growth was poor compared to growth usually seen when propagating citrus from seed. The trifoliate orange cuttings failed to strike, and the strike rate of the Valencia and Washington navel cuttings was very low.

Cuttings from the same source trees were collected, and single buds were chip budded into the stems. There were sufficient vigorous cuttings of Carrizo citrange, Eureka lemon, rough lemon, sweet orange and volkameriana to graft. The shoots on the cuttings of sour orange, Marsh grapefruit and Imperial mandarin were not suitable for grafting. Four months after grafting, there were 125 grafted and ungrafted cuttings suitable for transplanting into sand culture. The scion/rootstock combinations are set out in **Table 4**.

The difficulty of striking citrus cuttings has been pointed out. Nonetheless, nearly 3 years after collecting the cuttings, 124 plants of various citrus types on their own roots and grafted onto themselves or other citrus types are available (**Table 4**), but the age of the scion shoots varies considerably. This is due to the fact that shoot growth is being encouraged and allowed to harden off prior to the trees being cut back to force a new growth flush, the growth, mineral composition of which and leaf function will be dependent on the nutrient solution supplied, the roots and the scion.

Table 4 Numbers of scion/rootstock combinations in reciprocal grafting experiment

Rootstock	Scion					Root systems / genotype
	Carrizo citrange	Eureka lemon	rough lemon	sweet orange	Volk-ameriana	
own roots	2	8	6	8	5	29
Carrizo citrange	3	2	2	5	6	18
Eureka lemon	7	5	4	2	2	20
rough lemon	3	5	2	3	2	15
sweet orange	2	5	3	6	4	20
Volkameriana	2	4	6	7	3	22
Shoots / genotype	19	29	23	31	22	

As a result of the difficulties encountered in propagating and rearing these trees, the only investigation carried out on them was Dualex measurements on leaves. Not all plants had sufficient leaves for these measurements to be conducted, but where possible, measurements were conducted on the 3 youngest fully sized leaves on a new shoot and the 3 oldest leaves at the base of the previous growth flush.

Data analysis

All data sets were subjected to outlier detection using Grubbs' method (Rohlf and Sokal, 1981), and observations identified as outliers were eliminated from the data set. Variance homogeneity and normality were assessed, and appropriate transformations were applied to satisfy the assumptions underpinning analysis of variance. Where sources of variation had a significant F ratio of 0.05 or less, significant differences between means were identified using least significant differences (LSD) at P=0.05.

Results

Response of citrus rootstock seedlings to nitrogen supply

The relative vigour of the different rootstock genotypes was readily apparent at harvest (**Figure 3**). The trifoliate orange seedlings had significantly less dry matter than the other rootstocks, and volkamerina was the most vigorous. Between these extremes, the other four rootstocks fell into two groups, namely Swingle and sweet orange, and Troyer and macrophylla. The N supply main effects suggest that across all genotypes, maximum shoot dry matter production was attained by 4 mM.

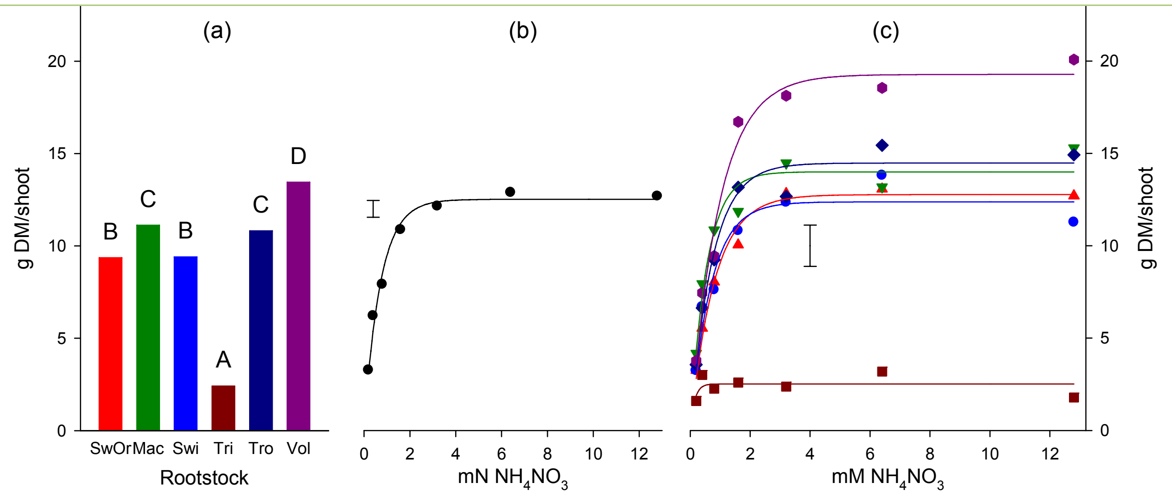


Figure 3 Genotype and N supply on citrus rootstock seedling shoot dry matter

(a) rootstock main effects, (b) N supply main effects, (c) rootstock × N supply interactions. Values presented are means (n = 70, 60 and 10 for rootstock, N supply and rootstock, respectively). Different letters above columns indicate significantly different means at P=0.05, and vertical bars represent LSD at P=0.05. Similar colours are used to represent the same rootstock genotypes in (a) and (c). An exponential rise-to-maximum function of the form: $f(x) = a(1 - e^{-bx})$, where x = mM N supply, and a and b are empirically determined parameters, was fitted to the N supply main effects' means in (b) and to each set of rootstock means in (c).

The parameters a and b of exponential rise to maximum function fitted to the NH_4NO_3 concentration versus dry matter at harvest plot for each genotype reflect the nature of each genotypes response to increasing N supply (**Table 5**). The a parameter equates to the maximum dry matter attainable for each genotype under the conditions of the experiment, and the b value is the inflection point for each curve. The nature of the function fitted means that the lower the value of b, the greater the rate of change in dry matter production as N supply increases. The non-significant regression for trifoliate orange aside, the responsiveness of the other five rootstock genotypes to increasing N supply could be ranked: volkameriana >

Troyer > Swingle > sweet orange > macrophylla. Maximum dry matter production of all rootstocks bar trifoliate orange was achieved with an NH_4NO_3 supply between 0.8 and 1.6 mM. Further increments in dry matter production in response to additional NH_4NO_3 supply were not observed possibly because other factors such as light or temperature were limiting. What distinguished the rootstocks was the rate of response to increments in N supply at low levels of supply.

Table 5 Regression parameters for mM NH_4NO_3 versus dry matter at harvest for 6 citrus rootstock genotype seedlings

See **Figure 3** for details of function fitted.

Genotype	*a*	*b*	Regression significance	Adjusted R^2
(All genotypes)	12.5	1.41	<0.0001	0.981
Sweet orange	12.8	1.63	<0.0001	0.979
Macrophylla	14.0	1.84	<0.0001	0.934
Swingle	12.4	1.46	0.0005	0.916
Trifoliate orange	2.5	7.00	0.264	0.089
Troyer	14.5	1.34	<0.0001	0.957
Volkameriana	19.3	1.04	<0.0001	0.974

Mean % N in the shoot dry matte at harvest across all rootstock genotypes was 1.81, and the large differences in dry matter production seen between the rootstocks was not apparent in the level of N in the shoots (**Figure 4**). The more vigorous rootstocks tended to have a lower % N in the dry matter, and the less vigorous rootstock had the highest % N in the shoot dry matter. Despite N supply varying by a factor of 64, shoot % N only varied by a factor of approximately two. Clearly, growth of the least vigorous rootstock was not limited by N supply, and growth of the most vigorous rootstock was equally not limited by N supply. Clearly also, most of the response to N supply occurred as N supply increased from 0.2 mM to 0.8 mM, possibly 1.6 mM.

To investigate the nature of this response, the amounts of N in the shoots were calculated using the shoot dry matter and % N data. On a rootstock basis, the amount of N in the shoots reflects the biomass to some degree (**Figure 5**). The N supply main effects suggested that the amount of N in the shoots when N supply was less than 2 mM increased linearly with each NH_4NO_3 concentration increment. Aside from the data for trifoliate orange, the slopes of the linear regression lines relating mg N in the shoot dry matter, as a function of N supply for each rootstock, were between 100 and approximately 200 mg N for each mM increment in NH_4NO_3 concentration. Across the rootstocks, the rate of response was not related to vigour, suggesting that one reason for the differences in vigour may involve the efficiency with which N is used by the leaves, possibly determined by the rate at which NO_3^- is converted to NH_2^- and subsequently incorporated into amino acids and protein. One indication of this may be gained from the levels of N still in the form of NO_3^- in the shoots.

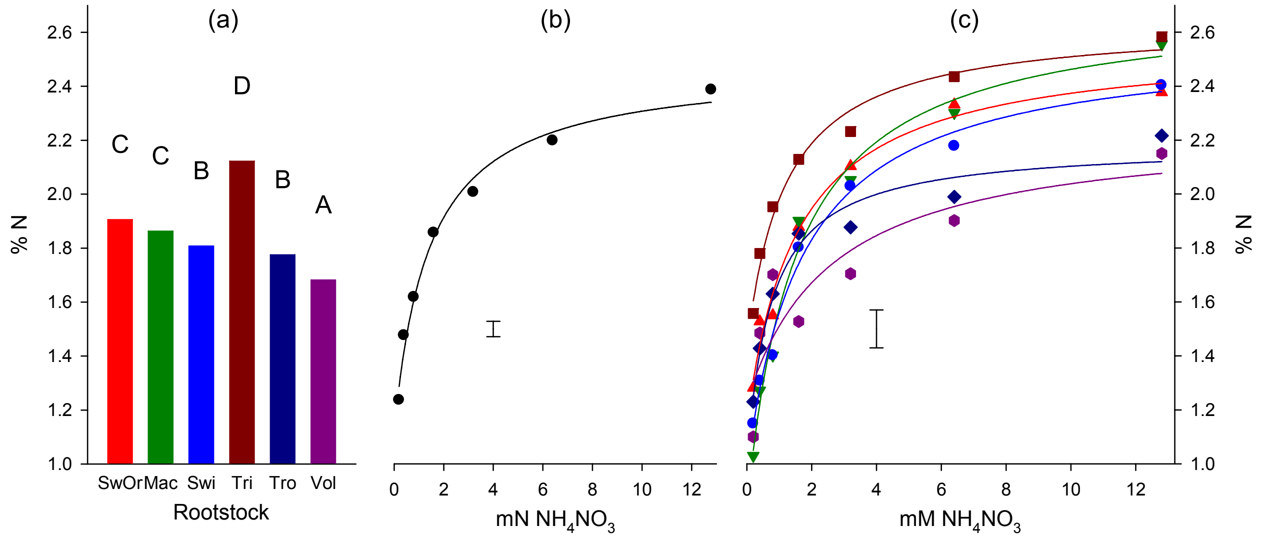


Figure 4 Effect of N supply on % N in shoot dry matter of six rootstock seedling genotypes at harvest

(a) rootstock main effects, (b) N supply main effects, (c) rootstock × N supply interactions. Values presented are means (n = 70, 60 and 10 for rootstock, N supply and rootstock, respectively). Different letters above columns indicate significantly different means at P=0.05, and vertical bars represent LSD at P=0.05. Similar colours are used to represent the same rootstocks in (a) and (c).

A 3-parameter rational function of the form,

$$f(x) = \frac{(1 + ax)}{(b + cx)},$$

where x = mM N supply, and a, b and c are empirically determined parameters, was fitted to the N supply main effects means in (b) and to each set of rootstock means in (c)

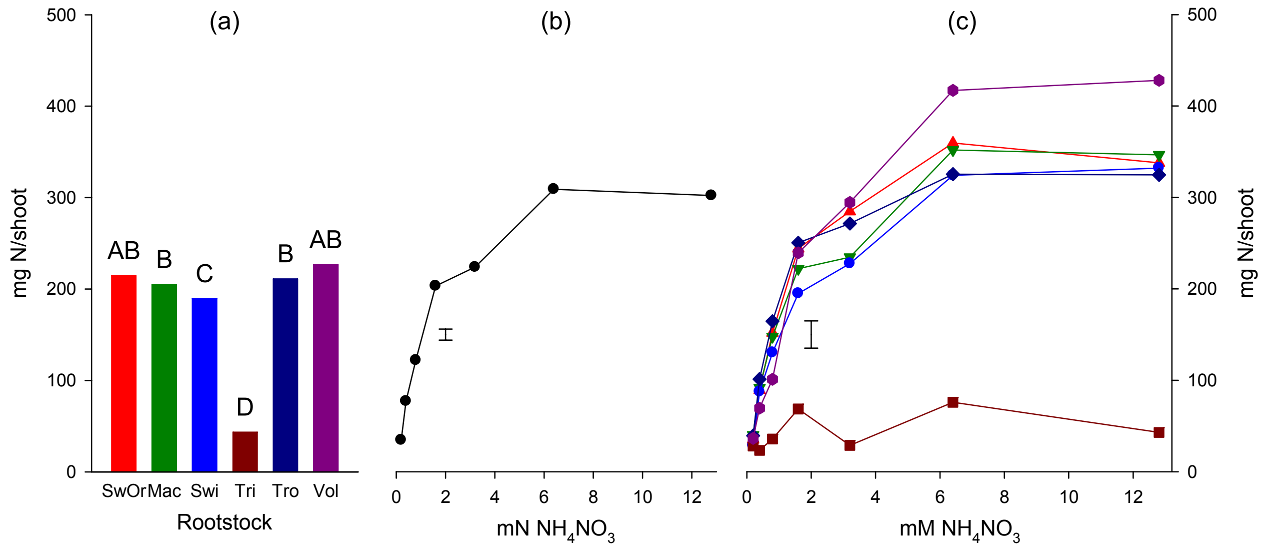


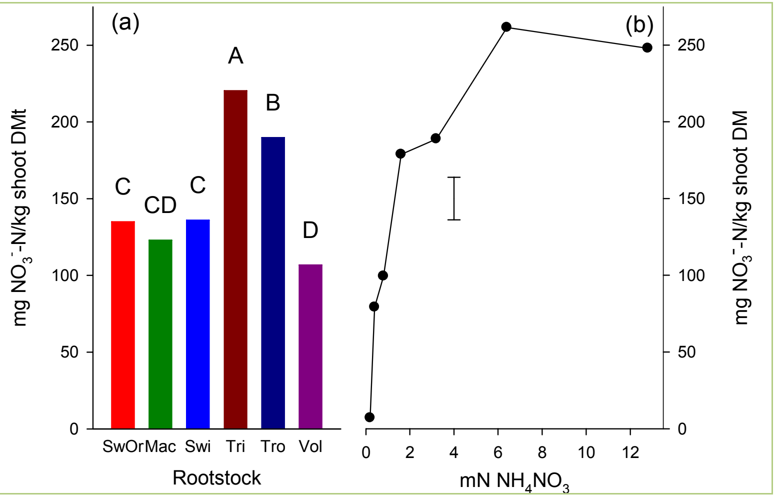
Figure 5 Effect of N supply on the quantity of N in the dry matter of shoots of six rootstock seedling genotypes at harvest

(a) rootstock main effects, (b) N supply main effects, (c) rootstock × N supply interactions. Values presented are means (n = 70, 60 and 10 for rootstock, N supply and rootstock, respectively). Different letters above columns indicate significantly different means at P=0.05, and vertical bars represent LSD at P=0.05. Similar colours are used to represent the same rootstock genotypes in (a) and (c).

Rootstock and N supply main effects on mg NO_3^--N content in the dry matter of shoots at harvest are presented in **Figure 6**. Apart from Troyer citrange, NO_3^--N levels in the shoots at harvest was inversely proportional to the rootstocks' vigour; the least vigorous rootstock had the highest level of oxidised N and the most vigorous rootstock the least. Thus the relative vigour of the rootstocks could in part be due to the efficiency of conversion of oxidised N into reduced N; a form of considerable importance to plant growth and development. The levels of NO_3^--N in the shoots of Troyer citrange are inconsistent with this model, and thus the vigour of this rootstock may be imparted by factors other than N metabolism.

Figure 6 Rootstock and N supply main effects on NO_3^--N in shoot DM at harvest

(a) rootstock main effects, and (b) N supply main effects. Values presented are means (n = 70 and 60 for rootstock and N supply, respectively). Different letters above columns indicate significantly different means at P=0.05, and vertical bars represent LSD at P=0.05.



Response of citrus rootstock seedlings to potassium supply

The batch of Swingle citrumelo seeds sourced for this experiment failed to germinate. Further, the growth of the trifoliate orange seedlings was exceptionally poor, and replanting with new seedlings did not result in better growth. It was concluded that the batch of trifoliate orange seeds was also defective in some way, and any data collected on those seedlings were not included in any analysis. Thus the design of this experiment (and the Si and pH experiments) featured four, not six, rootstock genotypes.

The effects of K^+ supply on shoot dry matter production, and shoot N, P and K are summarised in **Table 6**, **Table 7**, **Table 8** and **Table 9**, respectively.

Shoot dry matter production was maximised at 0.6 mM K^+ (equivalent to 23 mg K^+/L). There was no significant difference between dry matter production at half the optimal K^+ supply or twice the optimal rate. As observed in the N supply experiment, volkameriana seedlings were the most vigorous, but the lack of a significant rootstock by K supply interaction term suggested that all rootstocks responded similarly to K supply.

Mean % N in shoot dry matter ranged between 2.2 and 2.6 (**Table 7**). The K supply main effects suggested that a significantly lower % N in shoots of seedlings grown at 0.6 mM K^+ was only partially related to a growth dilution effect because the total amount of N in the shoots of seedlings grown at 0.6 mM K^+ was significantly higher than the total amount of N in the shoots of seedlings grown at either 0.3 or 1.2 mM K^+. Increasing K^+ supply did not affect % N in Troyer citrange shoots but lower % N in the shoots of sweet orange and volkameriana at 0.6 mM K^+ was consistent with a growth dilution effect to some extent. High K supply significantly increased % N in macrophylla shoots. Consistent with the vigour response, volkameriana shoots accumulated more N in the shoots at harvest than shoots of the other seedling rootstocks.

The rootstock by K supply interaction terms for %P and mg P/shoot were not significant, but rootstock main effects were, and K supply significantly affect %P (**Table 8**). Again, consistent with relative vigour of the rootstocks, volkameriana seedlings accumulated the most P. K supply did not affect the total amount of P in the shoots.

Shoot % K increased with increasing K supply (**Table 9**). The lowest % K was found in the shoots of the most vigorous rootstock, but the highest % K was measured in sweet orange seedlings, which were of comparable vigour to macrophylla and Troyer citrange.

A significant rootstock by K supply term for %K and lack of any significant interaction between rootstock and K supply on shoot biomass, highlights the differences in the response of each of the rootstocks to increasing K supply. All of the increase in % K in shoots of sweet orange occurred with the first increment in K supply. Conversely, increases in shoot % K in shoots of macrophylla and Troyer citrange occurred with the second increment in K supply. Volkameriana shoot % K was unaffected by K supply.

Table 6 Effect of K^+ supply on shoot dry matter production by four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within either main effect or within the interaction are not significantly different at P=0.05.

mM K^+	Rootstock: Sweet orange	Macro-phylla	Troyer citrange	Volk-ameriana	K supply main effects
	g/shoot				
0.3	8.7	8.0	7.9	10.0	8.7^{A}
0.6	10.9	10.3	7.8	16.6	11.4^{B}
1.2	8.0	7.6	7.0	11.1	8.4^{A}
Rootstock main effects	9.2^{A}	8.7^{A}	7.5^{A}	12.6^{B}	

Table 7 Effect of K^+ supply on % N and total shoot N of four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within either main effect or within the interaction are not significantly different at P=0.05

mM K^+	Rootstock: Sweet orange	Macro-phylla	Troyer citrange	Volk-ameriana	K supply main effects
	% N				
0.3	2.4^{B-D}	2.3^{AB}	2.6^{D}	2.5^{B-D}	2.5^{A}
0.6	2.2^{A}	2.3^{AB}	2.6^{D}	2.1^{A}	2.3^{B}
1.2	2.3^{A-C}	2.5^{CD}	2.5^{CD}	2.5^{B-D}	2.4^{A}
Rootstock main effects	2.3^{A}	2.3^{A}	2.6^{B}	2.4^{A}	
	mg N/shoot				
0.3	249	196	257	266	242^{A}
0.6	234	284	253	422	298^{B}
1.2	188	186	204	309	222^{A}
Rootstock main effects	224^{A}	222^{A}	239^{A}	333^{B}	

Table 8 Effect of K^+ supply on % P and total shoot P of four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within either main effect or within the interaction are not significantly different at P=0.05

mM K^+	Rootstock: Sweet orange	Rootstock: Macro-phylla	Rootstock: Troyer citrange	Rootstock: Volk-ameriana	K supply main effects
	% P				
0.3	0.26	0.19	0.26	0.24	0.24^{B}
0.6	0.21	0.20	0.23	0.24	0.22^{A}
1.2	0.23	0.21	0.26	0.23	0.23^{AB}
Rootstock main effects	0.23^{B}	0.20^{A}	0.25^{C}	0.24^{BC}	
	mg P/shoot				
0.3	21	15	26	24	22
0.6	13	8	12	30	16
1.2	12	8	15	35	17
Rootstock main effects	15^{A}	10^{A}	18^{A}	30^{B}	

Table 9 Effect of K^+ supply on % K and total shoot K of four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within either main effect or within the interaction are not significantly different at P=0.05.

mM K^+	Rootstock: Sweet orange	Rootstock: Macro-phylla	Rootstock: Troyer citrange	Rootstock: Volk-ameriana	K supply main effects
	% K				
0.3	1.1^{A-C}	1.2^{BC}	0.87^{A}	1.1^{A-C}	1.1^{A}
0.6	1.8^{D}	1.2^{C}	0.91^{AB}	1.2^{C}	1.3^{B}
1.2	1.7^{D}	1.6^{D}	1.3^{C}	1.3^{C}	1.5^{C}
Rootstock main effects	1.5^{A}	1.4^{B}	1.0^{C}	1.2^{B}	
	mg K/shoot				
0.3	60	42	25	127	64
0.6	149	103	80	118	113
1.2	95	62	65	198	105
Rootstock main effects	102^{AB}	69^{A}	57^{A}	148^{B}	

Effect of silicon supply on growth and N, P and K accumulation by citrus rootstock seedlings

As with the N and K supply experiments, rootstock genotype was the major source of variation in shoot dry matter production under varying Si supply treatments, and volkameriana seedlings were more vigorous than seedlings of the other three rootstock genotypes (**Table 10**). Overall, plants grown with 2 mM Si in the nutrient solution produced approximately one third less shoot dry matter compared to seedlings grown without added Si. There was no evidence that any rootstock genotype was more or less sensitive to the presence of 2 mM Si in the nutrient solution compared to any other genotype.

Table 10 Effect of 2 mM Si on shoot dry matter production by four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within either main effect or within the interaction are not significantly different at P=0.05. An * indicates a significant difference between Si supply means.

	Rootstock				
mM Si	Sweet orange	Macro-phylla	Troyer citrange	Volk-ameriana	Si main effects
			g/shoot		
0	10.8	12.2	9.6	18.7	12.8
2	6.7	7.0	7.0	11.4	8.0*
Rootstock main effects	8.7^{A}	9.6^{A}	8.3^{A}	15.1^{B}	

The effect of Si on shoot biomass production resulted in an increase in the concentration of N in the shoots because there was no significant effect of Si on the total amount of N accumulated by the shoots (**Table 11**). This suggests that the effect of Si on growth was not related to N uptake and transport.

Table 11 Effect of 2 mM Si on % N and total shoot N of four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within rootstock main effects are not significantly different at P=0.05. An * indicates a significant difference between Si supply means.

	Rootstock				
mM Si	Sweet orange	Macro-phylla	Troyer citrange	Volk-ameriana	Si main effects
			% N		
0	2.2	2.2	2.6	2.1	2.3
2	2.4	2.5	2.7	2.8	2.6*
Rootstock main effects	2.3^{A}	2.4^{A}	2.7^{B}	2.5^{AB}	
			mg N/shoot		
0	234	284	253	446	304
2	170	170	190	297	207
Rootstock main effects	202^{A}	227^{A}	222^{A}	371^{B}	

The effects of 2 mM Si on shoot P (**Table 12**) and shoot K (**Table 13**) were similar to the effect of 2 mM Si on shoot N; that is an overall concentration effect related to restricted growth, but some evidence that possibly for P the effect was more pronounced in sweet orange and Troyer citrange seedlings.

Table 12 Effect of 2 mM Si on % P and total shoot P of four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within rootstock main effects are not significantly different at P=0.05. An * indicates a significant difference between Si supply means.

	Rootstock				
mM Si	Sweet orange	Macro-phylla	Troyer citrange	Volk-ameriana	Si main effects
	% P				
0	0.21^{A}	0.20^{A}	0.24^{C}	0.24^{C}	0.23
2	0.23^{BC}	0.21^{AB}	0.29^{D}	0.24^{C}	0.24*
Rootstock main effects	0.22^{A}	0.21^{A}	0.27^{C}	0.24^{B}	
	mg P/shoot				
0	21	16	20	38	24
2	11	9	10	30	25
Rootstock main effects	16^{A}	12^{A}	15^{A}	34^{B}	

Table 13 Effect of 2 mM Si on % K and total shoot K of four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within rootstock main effects are not significantly different at P=0.05. An * indicates a significant difference between Si supply means.

	Rootstock				
mM Si	Sweet orange	Macro-phylla	Troyer citrange	Volk-ameriana	Si main effects
	% K				
0	1.2	1.3	0.99	1.3	1.2
2	1.7	1.9	1.3	1.6	1.6*
Rootstock main effects	1.4^{A}	1.6^{A}	1.1^{B}	1.4^{A}	
	mg K/shoot				
0	115	97	80	182	118
2	84	74	45	202	151
Rootstock main effects	99^{A}	85^{A}	62^{A}	192^{B}	

Effect of nutrient solution pH on growth and N, P and K accumulation by citrus rootstock seedlings

As with the K and Si supply experiments, the major source of variation in shoot dry matter production under different pH treatments was rootstock (**Table 14**), and volkameriana seedlings were more vigorous than seedlings of the other three rootstock genotypes. The nutrient solution pH had no effect on dry matter production by any of the rootstock seedlings or on %N in shoot dry matter at harvest (**Table 15**).

Table 14 Effect of nutrient solution pH on shoot dry matter production by four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within either main effect or within the are not significantly different at P=0.05

pH	Rootstock				pH main effects
	Sweet orange	Macro-phylla	Troyer citrange	Volk-ameriana	
	g/shoot				
6.3	10.8	12.2	9.5	20.0	13.2
7.7	14.1	10.7	11.3	14.4	12.7
Rootstock main effects	12.4^{A}	10.0^{A}	10.4^{A}	17.2^{B}	

More N was present in volkameriana shoots if the plants were growing in an acidic nutrient solution (pH of 6.3), even though volkameriana dry matter and % N were not significantly different between pH treatments, due to variability in the data. The amount of N present in the shoots of the other rootstocks was unaffected by nutrient solution pH.

Table 15 Effect of nutrient solution pH on % N and total shoot N of four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within rootstock main effects are not significantly different at P=0.05.

pH	Rootstock				pH main effects
	Sweet orange	Macro-phylla	Troyer citrange	Volk-ameriana	
	% N				
6.3	2.2	2.2	2.6	2.1	2.3
7.7	2.2	2.3	2.5	2.4	2.3
Rootstock main effects	2.2^{A}	2.3^{A}	2.5^{B}	2.2^{A}	
	mg N/shoot				
6.3	234^{A}	284^{A}	253^{A}	472^{B}	311
7.7	308^{A}	246^{A}	274^{A}	328^{A}	289
Rootstock main effects	271^{A}	265^{A}	263^{A}	400^{B}	

Both in terms of percentage in shoot dry matter and the amount present per shoot, the major influence on shoot P and K was rootstock (**Table 16** and **Table 17**). Shoot % K was higher if the seedlings were grown at pH 7.7 compared to 6.3.

Table 16 Effect of nutrient solution pH on % P and total shoot P of four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within rootstock main effects are not significantly different at P=0.05. An * indicates a significant difference between the nutrient solution pH means.

	Rootstock				
pH	Sweet orange	Macro-phylla	Troyer citrange	Volk-ameriana	pH main effects
	% P				
6.3	0.21	0.20	0.24	0.24	0.23
7.7	0.21	0.17	0.25	0.22	0.22
Rootstock main effects	0.21^{AB}	0.19^{A}	0.25^{C}	0.23^{BC}	
	mg P/shoot				
6.3	21	16	20	38	24
7.7	27	16	22	33	25
Rootstock main effects	24	16	21	36	

Table 17 Effect of nutrient solution pH on % K and total shoot K of four citrus rootstock seedling genotypes growing in sand culture

Values presented are means. Means followed by the same superscripted letter within rootstock main effects are not significantly different at P=0.05. An * indicates a significant difference between the nutrient solution pH means.

	Rootstock				
pH	Sweet orange	Macro-phylla	Troyer citrange	Volk-ameriana	pH main effects
	% K				
6.3	1.2	1.3	0.99	1.3	1.2
7.7	1.5	1.5	1.2	1.3	1.4*
Rootstock main effects	1.4^{A}	1.4^{A}	1.1^{B}	1.3^{A}	
	mg K/shoot				
6.3	115	97	80	182	118
7.7	188	132	91	194	151
Rootstock main effects	152	114	85	188	

Leaf phenolics assessment

There were a number of basic questions to be answered in relation to the use of the dual excitation fluorescence instrument.

Firstly, how reliable are the readings from day to day? Put another way, how similar are a set of readings taken within days of each other on the same leaves? This question was addressed by comparing measurements carried out on the same leaves (tagged) on two consecutive days using leaves on the seedling rootstocks in the N supply trial. A paired t-test across the 420 pairs of readings indicated that there was no significant difference between the readings on the same leaves on consecutive days. A graphical appreciation of this can be gained from **Figure 7**.

Figure 7 Scatterplot of Dualex readings on consecutive days conducted on tagged leaves of 6 citrus rootstock seedlings growing in sand culture over a range of N supply levels

The black dashed line represents 100% agreement between the 2 sets of readings (*i.e.* reading on June 16 = reading on June 15).

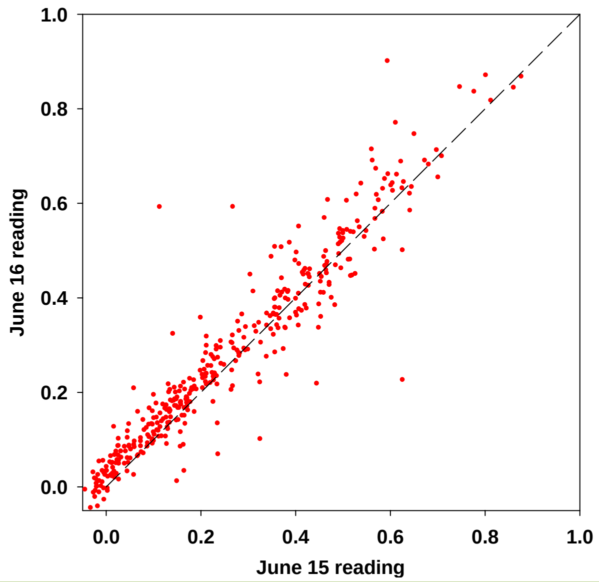
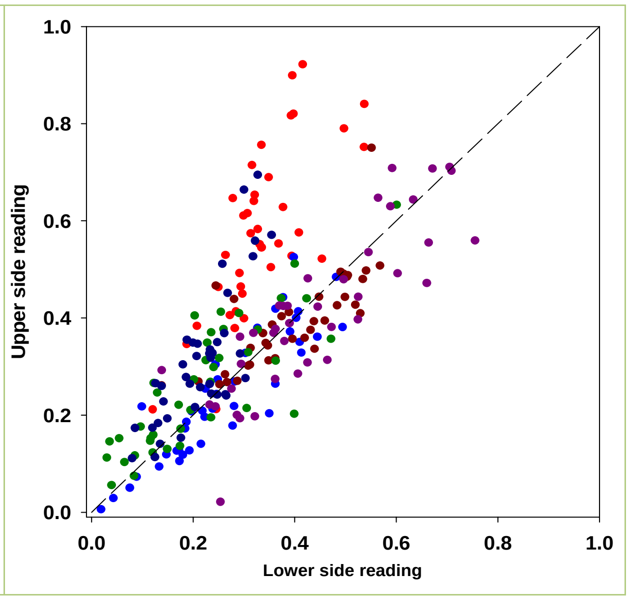


Figure 8 Scatterplot of Dualex readings on upper and lower sides of the same leaves on citrus rootstock seedlings growing in solution culture over a range of N levels

The black dashed line represents 100% agreement between the 2 sets of readings (*i.e.* reading on upper side = reading on lower side). Red, sweet orange; blue, macrophylla; dark brown, Swingle; dark green, trifoliate orange; dark blue, Troyer citrange; purple, volkameriana.



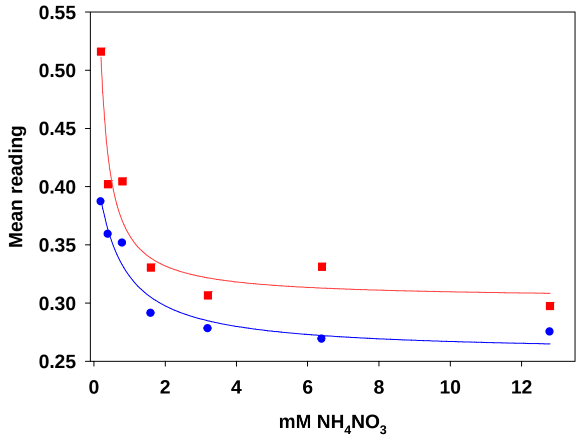
Secondly, stomate distribution is not uniform on the leaves of dicotyledonous plants such as citrus (Nobel, 2009). Thus, is it possible that different readings may be obtained by taking the reading on the upper side of the leaf versus the lower side of the leaf? This question was addressed by taking readings on the upper and the lower sides of the same leaves on the same day. The leaves were on the same rootstock seedlings used above, but these measurements were conduced about 4 months after the measurements used to establish the stability of readings on a day-to-day basis. A paired t-test of those data indicated that the mean readings were higher on the upper side than the lower side (0.37 *c.f.* 0.32). Further, analysis of variance suggested that the readings were only lower on the underside of leaves of sweet orange, trifoliate orange and Troyer citrange. This can be seen in **Figure 8** where pairs of reading for those rootstocks deviated the most from the 1:1 line.

Figure 9 Scatterplot of N supply main effects on mean Dualex readings from the upper (red) and lower (blue) leaf surfaces for 6 citrus rootstock seedlings growing in nutrient solution.

Values presented are means (n=36). Regression lines are exponential decay functions of the form:

$$y = ae^{\frac{b}{x+c}},$$

where y = mean reading, x = concentration of N in nutrient solution, and a, b and c are empirically determined parameters.



This analysis also indicated there was a significant interaction between N supply and the side of the leave on which measurements were conducted. The nature of this interaction can be seen in **Figure 9**.

The differences between mean readings and the slope of the regression functions at the lower end of the N supply range suggest that readings collected on the upper side of the leaf are more sensitive to N supply.

A summary of the impact of experimental variables on % N and C:N ratio of the whole shoot and on the Dualex measurements conducted on the youngest fully expanded leaf of each seedling rootstock on the day that the plants were harvested is presented in **Table 18**.

Generally, the experimental variable that influenced % N, C:N and Dualex readings the most was rootstock. Nitrogen supply accounted for most of the variation in shoot % N and C:N in the N supply experiment, but only accounted for 14% of the variation in Dualex reading. The presence of Si in the nutrient solution influenced both % N and C:N, but not the Dualex reading. Potassium supply influenced all three variables. Nutrient solution pH was not a significant source of variation for any of the three variables. The single largest factor influencing Dualex readings in all the trials was rootstock.

Plots of the mean shoot % N and C:N ratios versus the mean Dualex readings for the youngest fully expanded leaves for each treatment combination across all the experiments referred to above are presented in **Figure 10**.

The strength of the relationship between C:N and Dualex reading was marginally less than the strength of the relationship between % N and Dualex reading. Possibly this is related to the fact that % C varied between 43 and 47 %, and the analytical technique only provides whole numbers. That aside, variation in either shoot % N or shoot C:N accounted for approximately 50% of the variation in Dualex readings conducted on the youngest fully expanded leaf. Whole shoot N content is a function of months of uptake and transport and biomass accumulation. The N and phenolics content of the youngest fully expanded leaf, on the other hand, is more a function of uptake and transport over a much shorter period, and competition between the demand for carbon to grow and the need for N for protein to drive that growth during that much shorter period. Given those complications, the observation that shoot N and shoot C:N are significantly related to the Dualex reading on the youngest fully expanded leaf negatively and positively, respectively, suggests that the technology has potential to provide an estimate of the N status of citrus trees in real time.

Table 18 Summary of impact of experimental variables on whole shoot C:N and Dualex measurement conducted on the youngest fully expanded leaf on the day of harvest

		%N		C:N		Dualex reading	
Experi-ment	**Source of variation**	**F prob.**	**% variation**	**F prob.**	**% variation**	**F prob.**	**% variation**
N supply	**rootstock**	<0.001	10	<0.001	10	<0.001	30
	N	<0.001	77	<0.001	69	<0.001	14
	rootstock × N	<0.001	5	0.005	4	0.579	11
	error & unexplained	-	8	-	17	-	45
K supply	**rootstock**	<0.001	20	0.026	12	<0.001	55
	K	0.014	9	0.009	12	0.012	5
	rootstock × K	0.006	19	0.052	10	0.918	2
	error & unexplained		52	-	68	-	38
Si supply	**rootstock**	<0.001	32	<0.006	21	<0.001	68
	Si	<0.001	22	<0.001	28	0.099	4
	rootstock × Si	0.227	4	0.157	8	0.467	1
	error & unexplained		44	-	43	-	27
nutrient	**rootstock**	0.023	21	0.044	19	<0.001	63
	pH	0.678	<1	0.661	<1	0.792	<1
	rootstock × pH	0.419	6	0.689	3	0.782	1
	error & unexplained		72	-	77	-	35

Reciprocal grafting

The Dualex measurements conducted on leaves from the N, K and Si supply experiments and the pH experiment suggested that genotype was the strongest influence on the reading obtained from the youngest fully expanded leaf (Table 18, and previous section) of each plant. Measurements conducted on reciprocally grafted plants with suitable leaves indicated that grafting was generally associated with a reduction in the reading, and that grafting onto some genotypes had more impact than grafting onto others. The extent of these effects appeared to be greater in younger leaves than old, and, in general, the former had higher readings than the latter. The Dualex readings were inversely proportional to the tissue C:N ratio (see preceding section for further details). Younger leaves would be expected to have low C:N ratios as they expand and lay down cell walls *etc*. The lower Dualex reading on leaves on grafted plants suggests that the graft union is altering C partitioning in the growing shoot and/or is restricting nitrogen transport to the scion. Older leaves would be expected to have higher C:N ratios than younger leaves because there would be far more structural carbohydrates present in old leaves compared to young leaves. The Dualex readings were consistent with this hypothesis.

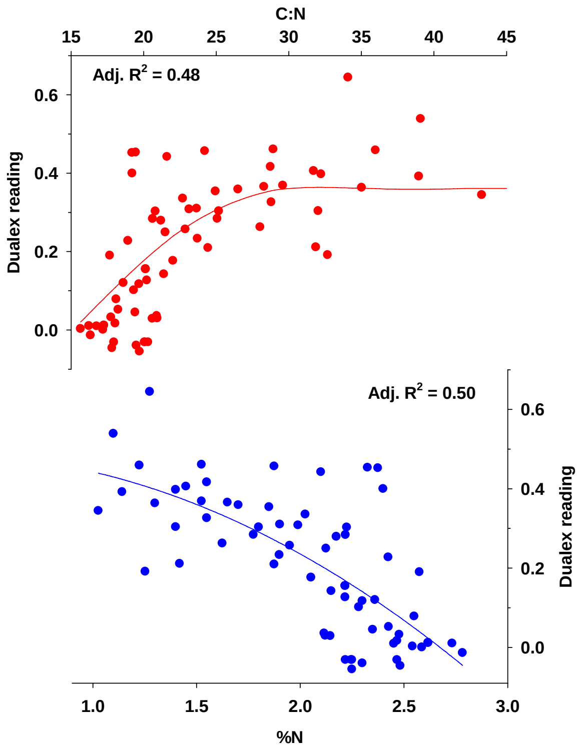


Figure 10 Scatter plots of shoot C:N versus Dualex reading (top) and shoot % N versus Dualex reading (bottom)

Values plotted are means of all treatment combinations in the rootstock×N supply, rootstock×K supply, rootstock×Si supply and rootstock×nutrient solution pH experiments

Discussion

With respect to N supply, growth was maximised with a concentration of 1.6 mM NH_4NO_3 in the nutrient solution which is equivalent to 45 mg N/L. Concentrations above this conferred no advantage in terms of shoot dry matter production, and only marginal increments in shoot %N. To put that concentration of N into some context, concentrations of N in the irrigation water supplied to the Atwood navel orange trees described in the "Impact of commonly practiced high-intensity fertigation regimes on yield and water, salt and nutrient movement within and below the root zone of navel oranges" section of this report were below this level in 2009-10, and higher than this level in 2010-11. Maintaining N concentrations in the soil solution at or below this level is challenging, particularly as soils dry out and if soil water is removed by tree roots faster than N is taken up by tree roots. Supplying N at concentrations in excess of 45 mg/L would make that challenge even more difficult. The important point is that N in the soil solution in excess 45 mg/L is less likely to be taken up by tree roots in the short term, and is therefore susceptible to loss from movement down the soil profile with wetting fronts associated with subsequent irrigations and from episodic rainfall events. The drop off in N uptake efficiency [*i.e.* $^{(\text{amount taken up})}/_{(\text{amount supplied})}$] associated with supplying the same amount of N in a few large doses versus many smaller doses has been described for young citrus in Florida (Scholberg *et al.*, 2002).

If 45 mg /L represents the highest concentration of N that needs to be in the soil solution to ensure that citrus tree growth is not limited by N supply, then some benchmark values for nitrate can be estimated using the proportion of total N in a fertigation program present in the nitrate form. For example, if all the N in a fertigation program was supplied as nitrate as, for example, potassium nitrate, then immediately after the fertigation event nitrate concentrations in the soil solution should not exceed 45 mg NO_3^--N/L or 200 mg NO_3^-/L. The longer the time period between the fertigation event and the extraction of the soil solution, the less relevant those bench mark values become because soil water and NO_3^- are not necessarily extracted at the same rate. Also it becomes more difficult to extract soil solutions as soil water is depleted.

If, on the other hand, ammonium nitrate (NH_4NO_3) was the sole source of N in the fertigation program, then immediately after a fertigation event the appropriate concentrations would be 23 mg NO_3^--N/L or 100 mg NO_3^-/L. This is due to the fact that the ratio of N in the form of NO_3^- to N in the form of ammonium (NH_4^+) in ammonium nitrate is 1:1. Those benchmark values become less relevant the longer the time period between application and soil solution sampling because of three concurrent processes:

1) NH_4^+ is converted to nitrate in soils by nitrifying bacteria,

2) both NO_3^- and NH_4^+ are taken up by the trees' roots, but not necessarily at the same rate, and

3) soil water may or may not be depleted at the same rate that either or both of the first two processes proceed.

If urea [$CO(NH_2)_2$] is the sole source of N in the fertigation program estimating the amount of N in the soil solution is more problematic. The two NH_2^- groups in urea are converted to ammonia (NH_3) which is either lost to the atmosphere or held in the soil. Ammonium is an intermediate product in this conversion. There is much less experience in Australia estimating either NH_4^+ or NH_3 in soil solutions although the methodology exists[3,4]. This is an area that warrants further investigation because for every 100 kg of urea added to the soil, 73 kg of CO_2 is unavoidably released and potentially 57 kg of NH_3 may be released as well. While the latter isn't considered a greenhouse gas, the former most certainly is. Urea is generally the most cost-effective source of N, and its use is attractive as a result. Therefore, managing that process to ensure that as much urea N remains in the soil as possible is important to offset the CO_2 unavoidably produced during the conversion of the N in urea to a form that tree roots can take up. Having quantitative means to assess the efficacy of any management decisions to achieve that aim would be helpful.

Before moving on, it is pertinent to point out here that the national water quality management strategy recommends a maximum of 11 mg NO_3^--N/L in the drinking water for bottle fed babies and 22 NO_3^--N/L for children and adults[5].

What distinguished the different rootstocks was the rate of response to increments in N supply at low levels of supply. This was reflected in the inflection points for the regression curve relating the concentration of N in the nutrient solution (independent variable) to shoot biomass for each rootstock (**Table 5**). The inflection points probably reflect differences in the uptake mechanisms and the efficiency of use of the N that is taken up (Sorgona *et al.*, 2006). Based on shoot biomass as an index of nitrogen use efficiency (Sorgona *et al.*, 2006), volkameriana is the most efficient and trifoliate orange is the least efficient. A component of that efficiency, namely the amount of N in the shoots, is of importance to scions growing on the rootstock. Clearly, volkameriana takes up and transports more N than the other rootstocks, and volkameriana shoots are more efficient in their use of that N than are the shoots of other rootstocks. The efficiency of use of N by grafted trees in the field will be a function of the amount of N taken up by the rootstock and transported to the scion, and the way that the scion uses that N for vegetative and reproductive biomass production.

Modifying the irrigation water/dissolved mineral fertiliser solution to pH 6.3 ("acid trimming") is a key part of the open hydroponics approach to managing water and nutrient

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[3] http://www.lamotte.com/pages/common/pdf/instruct/3680-01.pdf

[4] http://www.ysi.com/media/pdfs/A557-Quickly-Measure-pH-and-Ammonium-in-Aquaculture-Ponds-with-YSI-Pro-Plus.pdf

[5] http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/eh52_aust_drinking_water_guidelines_111130.pdf

supply to trees. Modifying the nutrient solution pH to 6.3 did not confer any advantage to seedling rootstocks growing in sand culture in terms of shoot biomass production or macronutrient accumulation. The comparison was made against seedling rootstocks growing in nutrient solution adjusted to pH 7.7; a pH not dissimilar to either soil pH or River Murray water pH. One rationale for the acidification of the irrigation water/dissolved mineral fertiliser solution may lie in the relationship between xylem fluid pH and stomatal activity (Wilkinson and Davies, 1997). Citrus xylem fluid pH becomes more alkaline under drought conditions, and stomatal aperture is reduced when apoplastic pH is above 7 (Forner-Giner *et al.*, 2011). Thus, the supply of an irrigation water/dissolved mineral fertiliser solution of pH 6.3 may maintain xylem fluid pH at about 6.3 despite changing soil moisture conditions, hence keeping stomates open and forcing transport of mineral nutrients to leaves and photosynthesis. However, for this hypothesis to be valid, greater biomass production should have been evident in the rootstocks seedlings growing in the nutrient solution adjusted to pH 6.3. This was not observed. Also, shoots of seedlings grown with pH 6.3 nutrient solution did not accumulate more macronutrients.

Responses to varying K supply were similar across the rootstocks, but, across all rootstocks, shoot biomass production was higher at 0.6 mM K^+ (equivalent to 23 mg K^+/L) than at 0.3 or 1.2 mM K^+. Possibly, this response was related to competition between cations (*i.e.* Ca^{2+}, Mg^{2+} and Na^+) during the uptake process, and a K^+ concentration of 0.6 mM resulted in suitably balanced uptake of all cations. Concentrations of K^+ in fertigation programs typically range between about 5 and 45mg/L (approximately 0.13 to 1.2 mM)

A real time estimate of tree N status would enable more informed and timely adjustments to N fertigation programs. There are a number of issues, however, that will need to be addressed before estimating tree N status in real time is feasible and citrus producers are able to use that information to assess the efficacy or otherwise of N fertigation programs.

Firstly, citrus trees bear leaves stemming from different growth flushes (Sauer, 1951), and there are, therefore, leaves of many different ages on each tree. Leaf function varies with leaf age as the leaves thicken, the leaf cuticle becomes thicker and the mineral nutrient content changes (Syvertsen, 1982; Syvertsen and Graham, 1990). The physical changes associated with leaf aging have hampered the development of such a tool based on leaf chlorophyll (Jifon *et al.*, 2005). Thus, any calibration exercise needs to be highly mindful of leaf age. An additional complication here is that levels of N in leaves are also affected by where on the tree the leaves arise (Koo and Sites, 1956). These issues can be overcome by highly structured studies and the identification and implementation of strict protocols.

Secondly, the Dualex readings need to be related to leaf N expressed on a specific leaf area basis (*i.e.* g N/m^2). This is because citrus leaves do not fix any additional CO_2 above a threshold amount of N per unit leaf area, despite the amount of chlorophyll increasing on a leaf area basis as the amount of N on the same basis increases (Bondada and Syvertsen, 2003). This type of comparison was not possible within the resources available to this project.

Thirdly, there is very little known about phenolic compounds in citrus leaves, in general. Phenolic compounds are involved in plants' response to biotic and abiotic stress (Mazid *et al.*, 2011). The linkage between soil fertility and the production of phenolic compounds in trees is a developing area of research (*e.g.* Kleczewski *et al.*, 2010) which has implications for how plants allocate carbon to achieve growth and defend against biotic and abiotic stressors. Thus, research on citrus in this area may produce knowledge that has application in plant protection, as well as serving to develop a means of estimating the efficacy of N supply regimes.

Impact of commonly practiced high-intensity fertigation regimes on yield and water, salt and nutrient movement within and below the root zone of navel oranges

Do "open hydroponics" approaches to water and fertiliser supply to citrus trees offer an advantage over well managed drip irrigation and a less intensive approach to supplying fertiliser using the drip system?

Summary

A trial comparing various combinations of drip irrigation (infrequent, daily and daily pulsed) and fertigation management (3-4 times per year and every irrigation event) was established in young Atwood navel orange trees at Dareton Primary Industries Institute. The trial also served as a demonstration site.

Treatments were applied for 3 seasons, and measurements carried out over the last 2 growing seasons, 2009/10 and 2010/11. Parameters measured included volume, EC and concentration of NO_3^- and K^+ in samples of soil solution drawn from 3 depths; concentration of nutrients in matured spring flush leaves; stem water potential; total number of fruit per tree and number of fruit within economically important size classes.

Electrical conductivity (EC) was found to not be a good surrogate for measurement of NO_3^- in soil solution, due to excessive noise in the relationship between the two parameters

Application of fertigation in frequent small doses reduced the incidence of spikes in NO_3^- concentration at 90 cm depth, which was below the rootzone of the trees. It is inferred that this fertigation management strategy therefore reduces the risk of leaching of fertiliser beyond the reach of tree roots. However, there was evidence of movement of NO_3^- to 90 cm depth in all treatments, indicating that leaching of nutrients is an ever present danger with any fertigation strategy.

Leaf tissue analysis results indicated that all treatments applied in this trial resulted in adequate nutrient uptake for the majority of nutrients.

Yield data indicated no significant benefit from very high frequency irrigation and fertigation ("open hydroponics") when compared to best practice drip irrigation and less intensive fertigation management.

Introduction

"Open hydroponics" is regarded as essentially soil-less hydroponics adapted to field conditions. The supply of water and nutrients is managed to strongly concentrate root growth under drip emitters (Falivene, 2005). The role of the soil is reduced to purely an anchoring medium. The approach is based on daily irrigations and daily injection of soluble mineral fertilisers. Feeder roots are concentrated in a very small area, and nutrient delivery needs to closely match the nutrient uptake by roots and crop requirement, to avoid potential losses of nutrients from the soil or chemical overloading of the soil Cote *et al.*, 2003.

This trial was established in 2008 to compare and demonstrate open hydroponics approaches alongside best practice drip irrigation and a less intensive approach to the supply of soluble mineral nutrients to young citrus trees. Measurements were made to evaluate the effectiveness of these approaches in supplying the nutrient requirements of citrus trees, and the movement of nutrients within and beneath the rootzone.

Materials and methods

Trial site

Atwood navel orange trees grafted on Troyer citrange seedling rootstock were planted in September 2004, at NSW DPI's Dareton Primary Industries Institute. The area had previously been planted to citrus, which had been removed 18 months previously, and the site fallowed in the intervening period using cereal cover crops. The site was a typical Mallee dune/swale landform, and most of the trial plantings were situated on the north facing aspect of the dune. The soil at the trial site was described as a Tiltao sand Northcote, 1951; a solonized brown soil (Gc1.2) falling within the calcic xerosol classification Northcote *et al.*, 1975.

Trees were planted 3.5 m apart in the row and 4.85 m between rows, giving a tree density of 589 trees/ha. Treatments were applied to plots of 5 trees within a row, but only the 3 middle trees in each plot were measured, the first and last trees in each plot acting as buffer trees.

Treatments

Five treatments were applied (**Table 19**):

❶ Control (best practice conventionally managed drip irrigation based on RAW/ETo scheduling and annual mineral nutrient needs supplied in 3-4 doses per irrigation season applied during spring and summer;

❷ Conventionally managed drip irrigation with fertiliser supplied during every irrigation;

❸ Daily pulsed (up to 6 pulses/day) drip irrigation with annual mineral nutrient needs supplied in 3-4 doses per irrigation season applied during spring and summer;

❹ Daily pulsed (up to 6 pulses/day) drip irrigation with fertiliser supplied during every irrigation;

❺ Daily continuous drip irrigation with fertiliser supplied during every irrigation.

Table 19 Combinations of drip irrigation and fertiliser management applied to young Atwood navel oranges

Frequency of fertiliser supply *via* drip irrigation water during irrigation season	Irrigation frequency		
	ca. weekly	daily	daily
		Strategy	
		pulse	continuous
× (3-4)	❶	❸	-
every irrigation	❷	❹	❺

Although each treatment was applied in a 5 × 5 Latin square layout, there were, from a biometric viewpoint, two trials:

- an irrigation frequency (*i.e.* ❶ and ❷ *versus* ❸ and ❹) × fertiliser supply frequency (*i.e.* ❶ and ❸ *versus* ❷ and ❹) interaction trial, and
- an irrigation frequency (*i.e.* ❷ *versus* ❹ *versus* ❺) trial using trees that were supplied fertiliser in every irrigation event.

Irrigations were scheduled using data from the Australian Government's Bureau of Meteorology and commercial providers of weather forecasts, and considering soil moisture measurements from tensiometers (15, 30 and 60 cm) installed in two of the trial plots. Field capacity and refill point were set at -5 and -15 kPa, respectively. Two drip lines were used, one either side of the tree row, with in-line emitters spaced 0.7 m apart. Two emitters on each line between the trees were blocked, giving a total of 6 drippers per tree. Irrigations were controlled by a Netafim NMC-Junior controller and NMCnet software.

The mineral nutrition program was based on a combination of nutrient removal rates, industry and empirical experience and tree phenology (**Table 20**).

Dissolved mineral nutrients were supplied to the conventional treatment using a Netafim® sealed tank system. Nitrogen was mostly applied as pre-dissolved urea and ammonium nitrate, phosphorus as a liquid polyphosphate formulation and potassium as potassium sulphate in either pre-dissolved liquid form or solid which was then dissolved. All liquid formulations used were supplied by SprayGro®.

Dissolved mineral fertilisers were supplied to the daily fertigation treatments using an improvised twin tank system and Dosatron® injection pumps. The first tank contained a solution of calcium nitrate, magnesium nitrate and chelated micronutrients. The second tank contained a solution of potassium sulphate, potassium nitrate, ammonium nitrate and monoammonium phosphate, adjusted to pH 6.0-6.5 using SprayGro® Reducer.

Sampling and measurements

Soil solution sampling tubes were installed in each of the 25 plots, on the eastern side of the tree row 0.5 m from the trunk of the middle tree in each plot, at depths of 20, 50 and 90 cm. Depending on the time of year, soil solutions were extracted every 2-6 weeks. The volume of fluid collected was determined gravimetrically (assuming 1 mL of fluid ≡ 1 g), and, volume permitting, pH and electrical conductivity (EC) determined using Eutech handheld pH and EC testers calibrated against standards. Again, volume permitting, NO_3^- concentration was evaluated using Merck test strips with an RQflex meter and K^+ concentration was measured using a Horiba Cardy meter.

Leaf samples were collected in February each year as per industry practice Robinson *et al.*, 1997 to determine tree mineral nutrient status. Mineral analyses were conducted at NSW DPI's Wollongbar research facility.

Stem water potential was measured with a Shölander pressure chamber (Model 3000; Soil Moisture Equipment Corp., Santa Bárbara, California, USA) in the afternoon between 13:00 and 15:00 h on non-transpiring leaves close to the stem Naor and Cohen, 2003. Leaves were bagged with both plastic sheet and aluminium foil at least 2 h before measurement to prevent leaf transpiration, so leaf water potential equalled stem water potential Begg and Turner, 1970. The water potential was measured monthly in two leaves from the one tree for each treatment and replicate.

Fruit were harvested in July of each season and total number of fruit per tree recorded. Fruit size distribution was determined using a Vision Systems automatic fruit grader, which consigned each fruit to a particular size class corresponding to the number of fruit that would be packed into 20L cardboard fruit boxes in a commercial packing planting. Only the data for the middle tree in each plot were used for analysis.

Results

Water supply

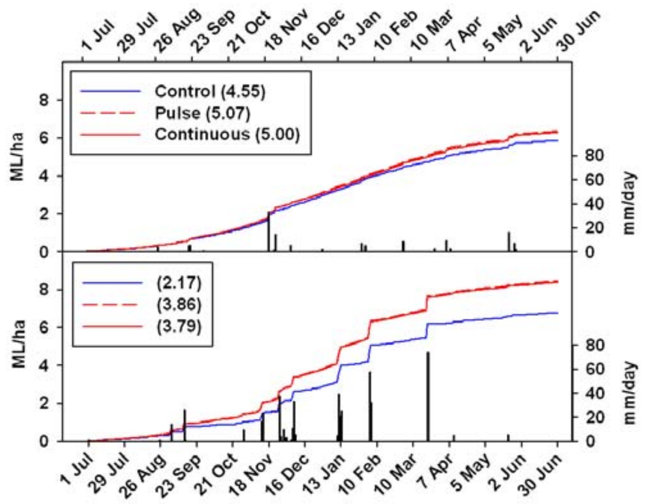
The effective rain and cumulative water supply profiles for each season are presented in **Figure 11** for the 2009-10 and 2010-11 irrigation seasons. Also presented are the total amounts of water supplied via irrigation for each season. The 2009-10 season was much drier than the following season, and so the total amount of water supplied as irrigation was higher in that season compared to the wetter season. Across all treatments the total amount of water applied from both sources was about 6.2 ML/ha in the dry season and 7.8 ML/ha in the wetter season. Across all methods of managing drip irrigation used in the trial an average of 4.8

ML/ha was supplied as irrigation water in the drier season, and about 3.2 ML/ha in the wetter season.

Figure 12 shows graphically the seasonal pattern of irrigation applications in response to changing crop water requirement. In the summer months irrigations were more frequent in the control treatment, and daily irrigations were larger in the pulse and continuous treatments, reflecting increased demand for water compared to the winter months. Note that the frequency of irrigation events was much lower in the 2010-11 irrigation season than the 2009-10 season, due to the greater incidence of effective rainfall events (see Figure 11).

Figure 11 Effective rainfall (vertical bars) and cumulative total water supply to drip-irrigated Atwood navel oranges managed conventionally (control) or dripped daily for a continuous period or using short pulses

Upper panel, 2009-10; lower panel, 2010-11. Numbers in brackets are the amounts of water supplied *via* irrigation (ML/ha/season).



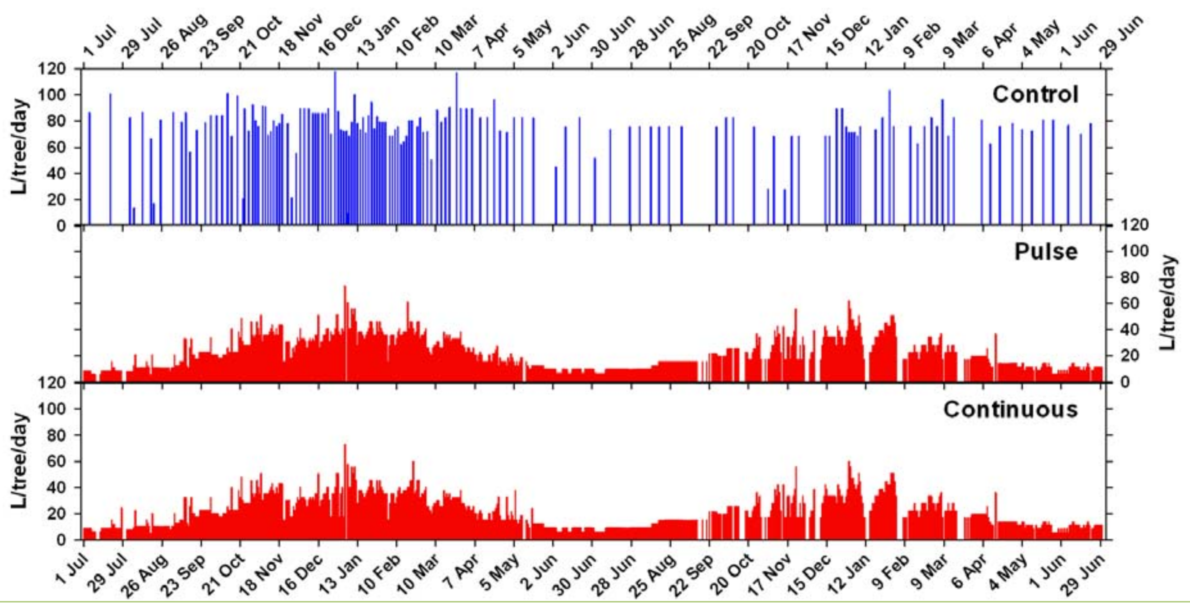


Figure 12 Daily water supply to Atwood navel orange trees as a function of drip management over 2 irrigation seasons (July 2009 to June 2011)

Fertiliser supply

The seasonal mineral nutrient supply to the trees as a function of treatment is summarised in Table 20. The differences in the amounts supplied between seasons and between treatments relate to the maintenance of constant concentrations of nutrients in the irrigation water over certain periods of time, and the differences in the amounts of water supplied to each of the drip irrigation management treatments. Fertiliser supply was increased in the 2010-11 season to account for the additional nutrient needs of the larger trees (compared to 2009-10), which were carrying a heavier crop load (compared to 2009-10).

Table 20 Seasonal and average mineral nutrient supply to Atwood navel orange trees over 2 drip irrigation seasons (July 2009 to June 2011)

	Drip irrigation management	Fertiliser scheduling	Mineral nutrient					
			N	P	K	Ca	Mg	S
			kg/ha					
2009/10	control	control	68	62	14	140	0	77
	pulse	control	68	62	14	140	0	77
	pulse	daily	76	11	49	46	0	0
	continuous	daily	76	11	49	46	0	0
	control	daily	68	10	44	43	0	0
2010/11	control	control	127	14	54	0	0	54
	pulse	control	127	14	54	0	0	54
	pulse	daily	139	15	89	93	5	3
	continuous	daily	139	15	89	93	5	3
	control	daily	55	7	34	44	3	2

Soil solution composition

An appreciation of the variability in the volume of soil solution extracted and the composition of that soil solution can be gained from Figure 13, where means and standard deviations for irrigation management, fertiliser management, soil solution sampler depth and sampling date are presented. The entire dataset was characterised by extreme variability, demonstrated by the large standard deviations, even after elimination of outliers. Bearing that proviso in mind, it can be said, however, that on average across the entire trial, approximately 10-12 mL of soil solution could be extracted, and that neither irrigation management nor fertiliser management appeared to influence the volume extracted. Nitrate concentration in the soil solution was much lower in winter than summer, but concentration in summer was extremely variable.

It also needs to be pointed out that there was not a complete record for any individual ceramic sampler. In other words, every sampler on at least one sampling date failed to provide any soil solution. This feature of the dataset precluded time series analysis which would have been the most appropriate method of assessing differences in soil solution composition over time and relating those differences to the treatments being applied.

Soil solution EC and NO_3^- concentrations are considered to be closely related, and EC is sometimes used as a means of estimating NO_3^- in soil solution because it is much simpler and less time consuming than measuring NO_3^-. Scatter plots of mg NO_3^-/L versus EC for soil solution samples extracted at 20, 50 and 90 cm are presented in **Figure 14**. The plots and regression analysis indicate that EC is positively influenced by the concentration of NO_3^- in the soil solution, but the strength of that influence diminishes deeper down the profile. Also, at soil NO_3^- levels of interest to citrus producers (*i.e.* < ~200 mg/L) there is considerable variability in the relationship, which suggests that EC is a relatively poor surrogate for estimating soil solution NO_3^- levels.

The impact of irrigation method on NO_3^- concentration in the soil solution is demonstrated in **Figure 15**. The data comes from treatments 2, 4 & 5, all of which were based on fertigation with every irrigation event.

Generally, NO_3^- levels rose as the cumulative amount of N supplied rose, and declined when supply ceased. It is clear from the graphs that NO_3^- moved through the soil profile quickly, appearing at the 90cm depth soon after it appeared at 20 and 50 cm depths in both seasons. This is despite the fact that concentrations of NO_3^- at 20 and 50 cm depths were not excessive, and demonstrates the difficulties of maintaining suitable concentration of NO_3^- in the rootzone, to facilitate uptake by roots, without contributing to significant leaching beyond the rootzone.

Spikes in NO_3^- concentration in the second season may be caused by low water content of the soil at the time of sampling, or nitrification variability. There is no other obvious explanation for these spikes in the pattern of NO_3^- application.

The impact of fertigation method is demonstrated in **Figure 16**. The data come from treatments 1, 2, 3 & 4, and represent weekly (control) vs. daily pulsed irrigation (pulse), and fertigation in a few large doses throughout the year (control) vs. fertigation every irrigation (proportional).

The data clearly demonstrates the impact of applying fertiliser in a few large doses on concentration in the soil solution. The highest peaks in concentration of NO_3^- occur in treatment 1 (control/control), which received less frequent irrigation and fertigation. Looking specifically at the 90 cm depth, where peaks represent leaching events, leaching is apparent in the two control fertigation treatments in the first season, especially associated with the application of a large dose of fertiliser in January. Leaching is also apparent in treatment 1 (control/control) in the second season. Interestingly, in the second season it appears that leaching also occurred early in the season from the pulse/proportional treatment, most likely as a direct result of the high amount of fertiliser applied at this time.

Tree nutrient status

Comparison of nutrient levels in matured spring flush leaves collected from non-fruiting terminals in February each year with interpretative standards (Robinson et al., 1997) indicates that generally the trees were in the adequate range for most nutrients (**Figure 17**). Nitrogen content of leaves ranged from marginal to high, indicating that fertigation rates were generally more than adequate.

Irrespective of which subset of the data were analysed, season was the largest contributor to variation in tree nutrient status, as measured by analysis of spring flush leaves sampled in February. For example, in the drip irrigation management trial (**Table 21**) there were significant differences between seasons for 11 out of 13 nutrients, but significant differences were found between drip irrigation management treatments for only 2 out of 13 nutrients (Cl^- & Fe).

Table 21 Main effects of season and drip irrigation management on navel orange tree nutrient status

Values presented are means (season, n=15; irrigation, n=5), and different superscripts within seasons or within irrigation management indicate significant differences between means (P=0.05).

Nutrient	Season			Drip irrigation management		
	2008	2009	2010	Control	Pulse	Continuous
			%			
N	2.6[b]	2.5[a]	2.8[c]	2.6	2.7	2.7
P	0.12[a]	0.13[b]	0.13[b]	0.12	0.13	0.13
K	1.15[a]	0.98[b]	1.00[b]	1.04	1.05	1.03
Ca	5.8[a]	5.9[a]	5.0[b]	5.7	5.6	5.5
Mg	0.38[b]	0.42[c]	0.35[a]	0.38	0.39	0.38
S	0.25[a]	0.23[a]	0.28[b]	0.25	0.25	0.25
Na	0.014[a]	0.009[b]	0.008[b]	0.011	0.010	0.011
Cl	0.05[a]	0.09[b]	0.07[a]	0.08[b]	0.06[a]	0.08[b]
			mg/kg			
B	80	87	95	90	94	77
Cu	6.4[b]	8.4[c]	4.1[a]	7.1	6.0	5.8
Fe	115	115	126	128[b]	111[a]	117[ab]
Mn	20[a]	25[b]	27[c]	24	23	24
Zn	6.1[a]	10.0[b]	12.2[c]	9.7	9.5	9.1

The effect of pulsing irrigation on tree Cl^- and Fe status was also observed in the drip irrigation × fertiliser management trial (**Table 22**), but, again, the effect was not large. There was only one nutrient for which significant interactions were observed; under conventional fertiliser management pulse drip was associated with slightly lower leaf K, but the difference would not be considered of practical significance.

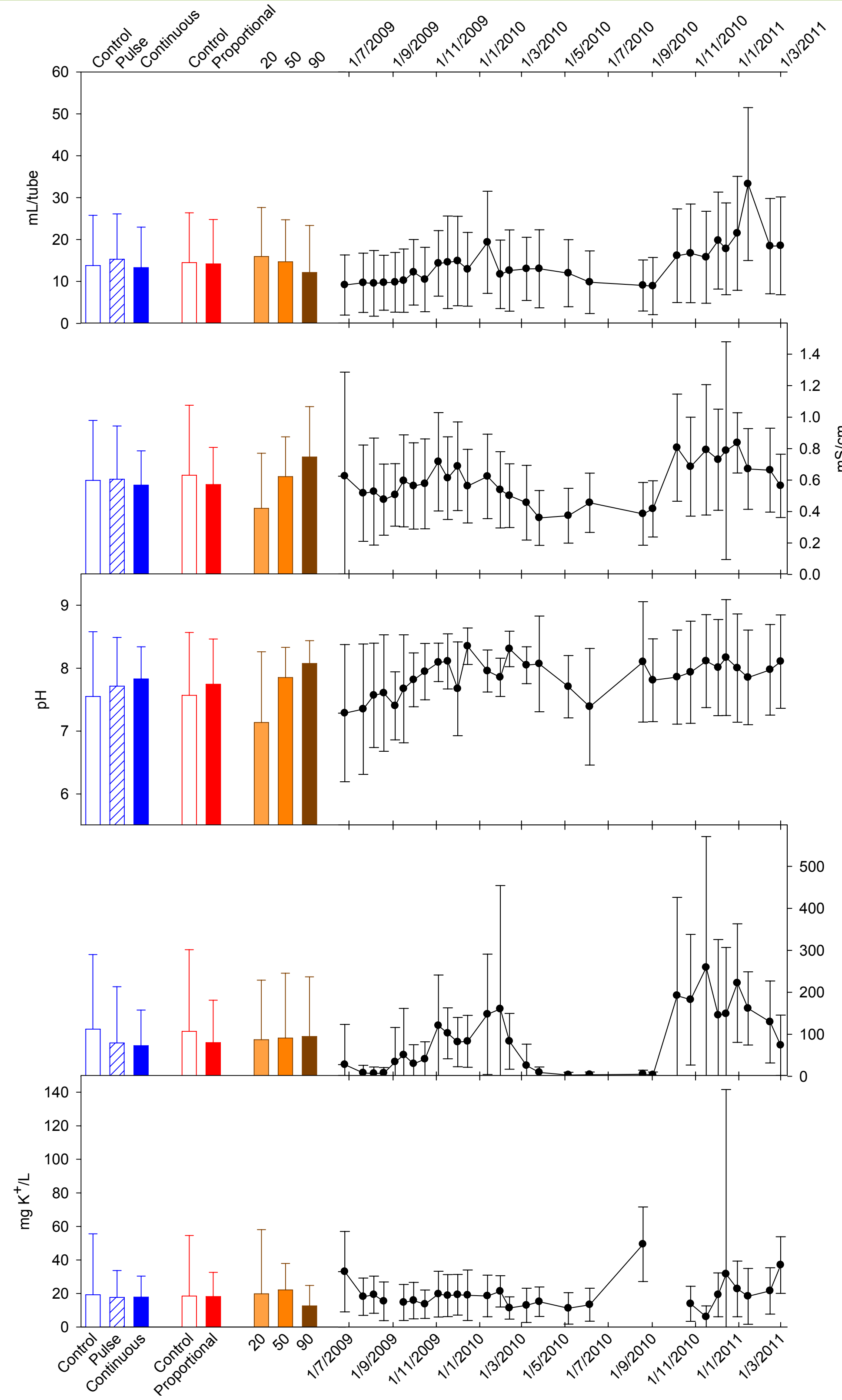


Figure 13 Irrigation management, fertiliser management, soil solution sampler depth and sampling date main effects on volume of soil solution extracted and the electrical conductivity , pH and NO_3^- and K^+ levels in the soil solutions extracted

Values presented are means across the entire trial. Vertical bars represent ± 1 standard deviation.

Figure 14 Scatter plots of NO_3^- versus EC of soil solutions extracted at 3 depths in the drip irrigated Atwood navel orange experimental orchard at Dareton over 2 seasons (2009-10 & 2010-11)

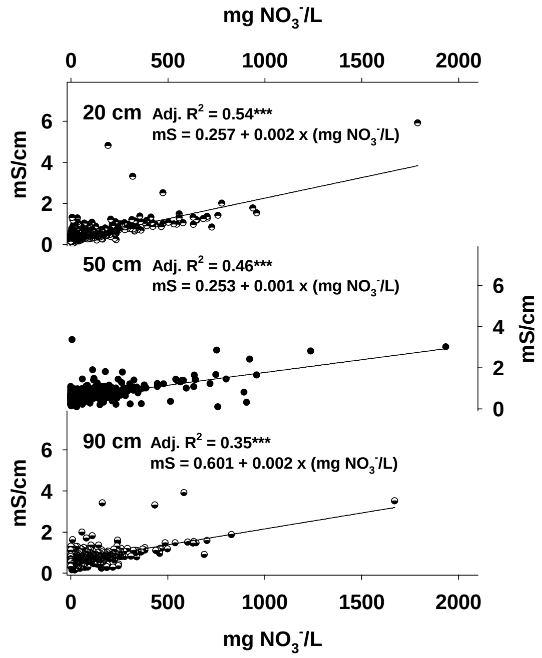
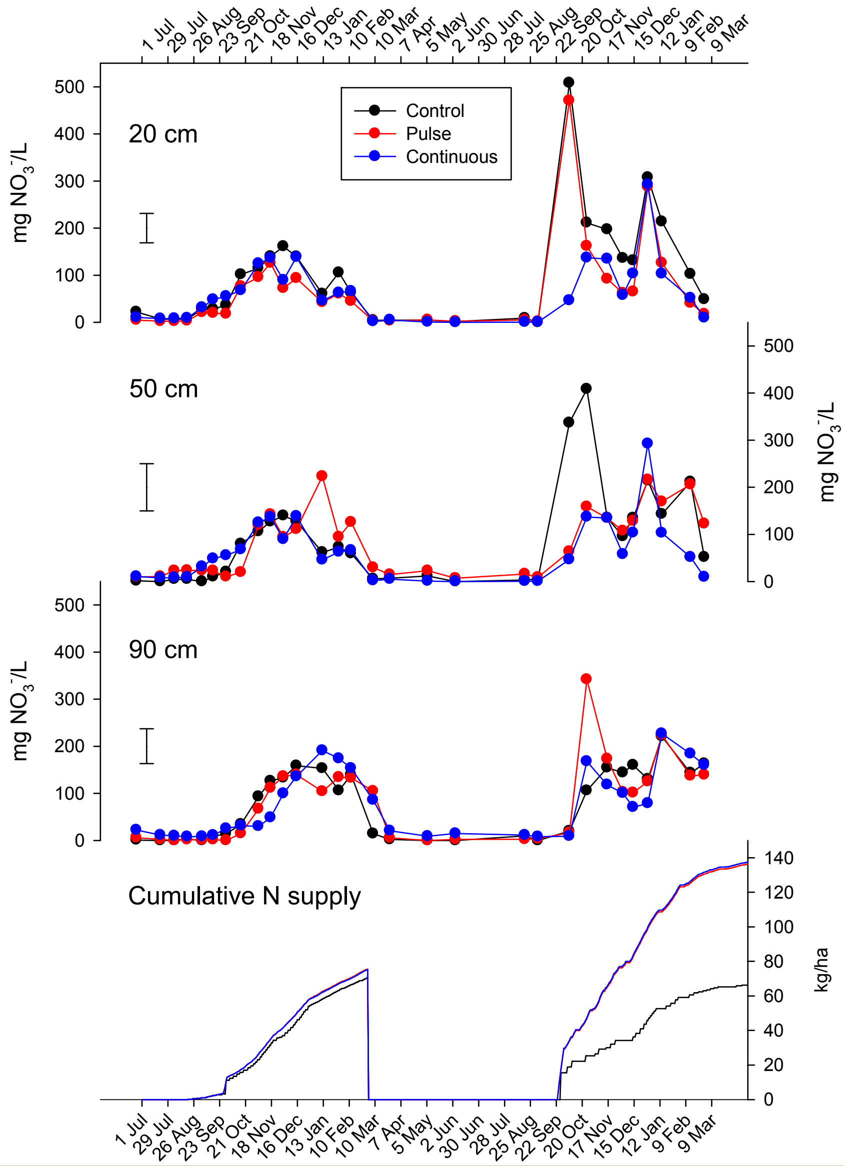


Figure 15 Effect of drip irrigation management on NO_3^- concentrations in soil solutions extracted from 3 depths in the Atwood navel orange experimental orchard at Dareton, cumulative N supply to each irrigation treatment and effective rainfall (2009-10 & 2010-11)



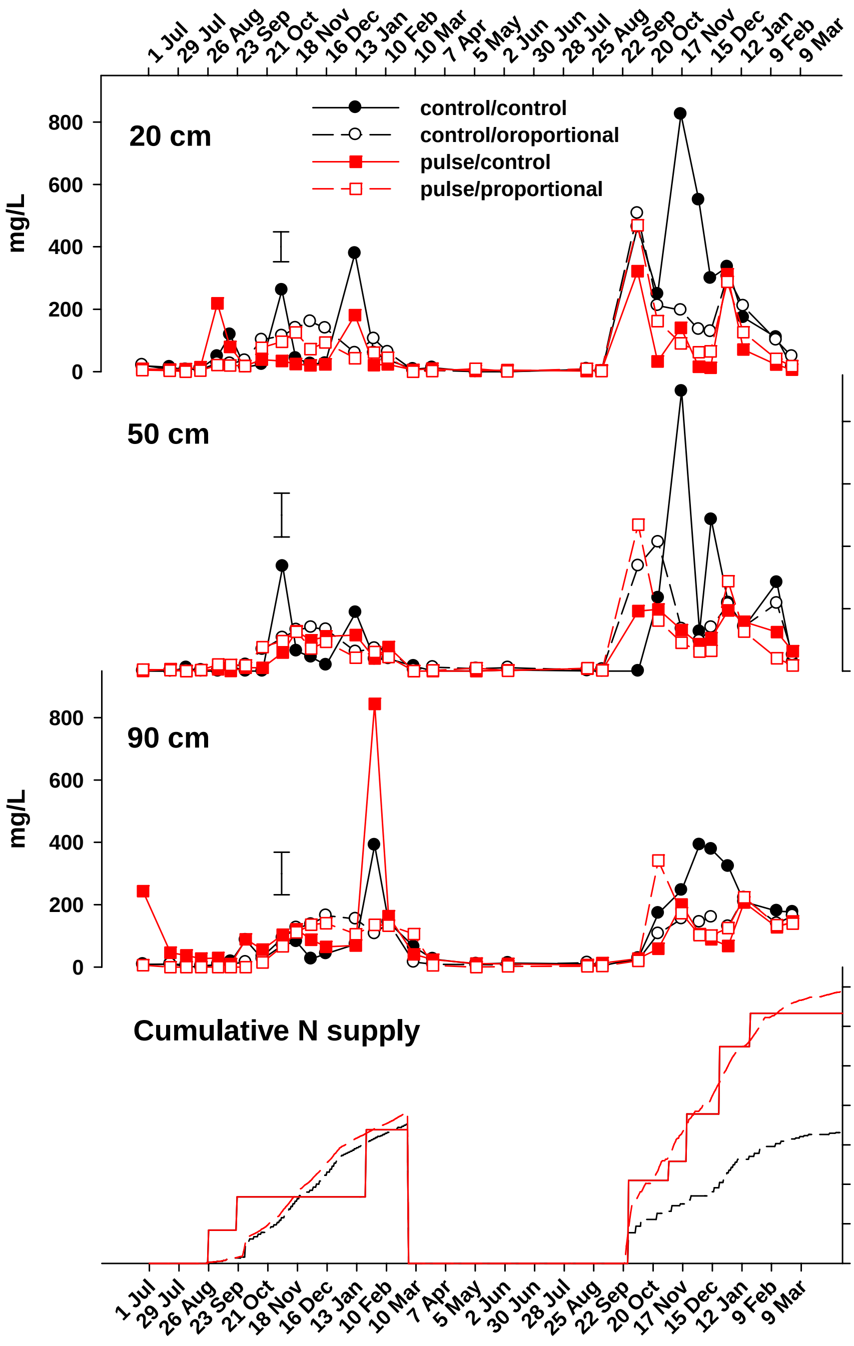


Figure 16 Effect of drip irrigation management and fertiliser supply management on NO_3^- concentrations in soil solutions extracted from 3 depths in the Atwood navel orange experimental orchard at Dareton, and cumulative N supply to each irrigation treatment combination (2009-10 & 2010-11)

Note that the cumulative supply of N to the pulse/control trees (solid red line) overlays the cumulative supply of N to the control/control trees.

Figure 17 Minimum, mean and maximum nutrient levels in mature spring flush leaves from non-fruiting terminals sampled in February, and diagrammatic representation of interpretative standards for citrus

Black dots represent, from left to right, minimum, mean and maximum observations over three seasons, and the colours represent deficient (yellow), marginal (light green), adequate (dark green), high (orange) and toxic/excessive (red) (based on and adapted from Robinson *et al.*, 1997).

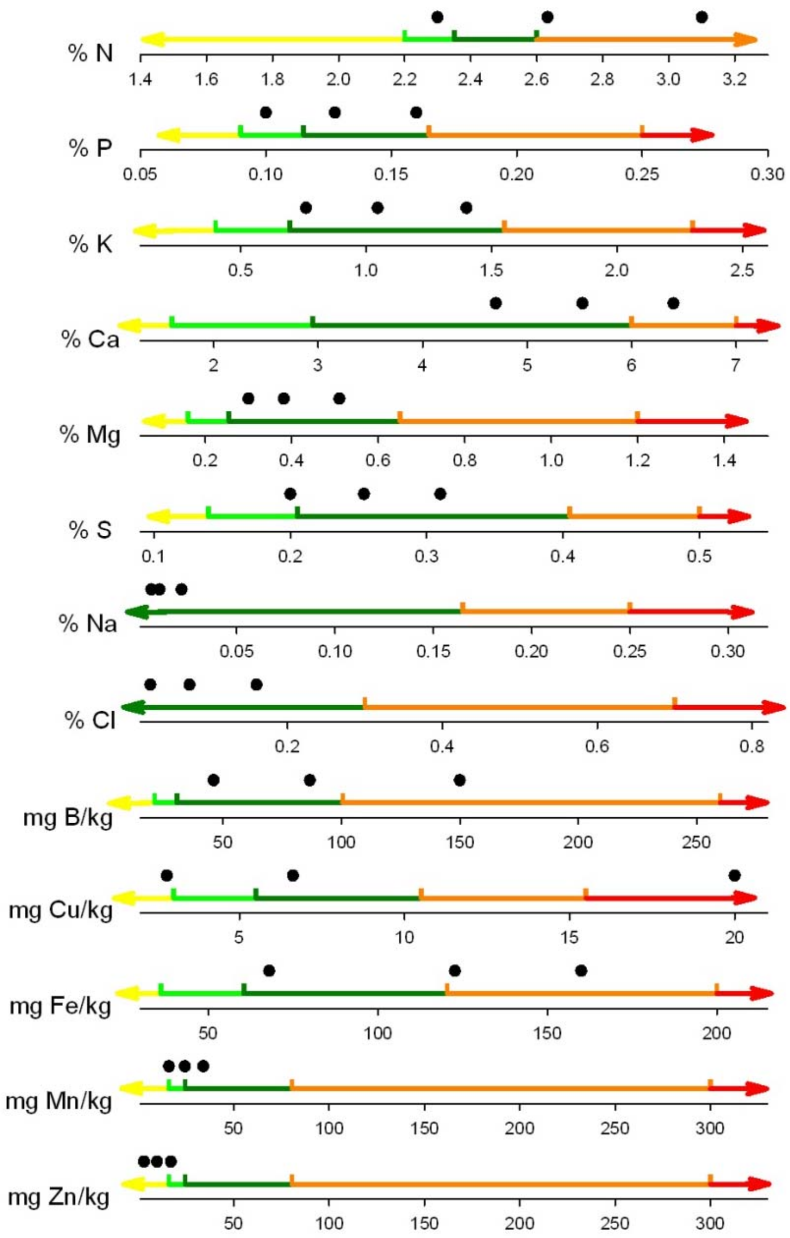


Table 22 Effect of irrigation and fertilisers supply (via irrigation) on navel orange tree nutrient status

Values presented are means (irrigation × fertiliser interaction: n=15; irrigation management main effect: n=30; fertiliser management main effect: n=30).

		Fertiliser			Fertiliser		
		Control	Prop^{n}	Average	Control	Prop^{n}	Average
		——% N——			——% Na——		
Drip management	Control	2.6	2.6	2.6	0.011	0.011	0.011
	Pulse	2.6	2.6	2.6	0.010	0.010	0.010
Average		2.6	2.6		0.011	0.011	
		——% P——			——% Cl——		
Drip management	Control	0.13	0.12	0.13	0.08	0.08	0.08
	Pulse	0.13	0.13	0.13	0.08	0.06	0.07*
Average		0.13	0.13		0.08	0.07	
		——% K——			——mg B/kg——		
Drip management	Control	1.11^{a}	1.04^{ab}	1.08	92	90	91
	Pulse	0.98^{b}	1.05^{ab}	1.01*	80	94	87
Average		1.05	1.05		86	92	
		——% Ca——			——mg Cu/kg——		
Drip management	Control	5.4	5.7	5.6	7.1	7.1	7.1
	Pulse	5.5	5.6	5.5	7.0	6.0	6.5
Average		5.4	5.6*		7.1	6.5	
		——% Mg——			——mg Fe/kg——		
Drip management	Control	0.37	0.38	0.38	131	128	130
	Pulse	0.38	0.39	0.39	128	111	119*
Average		0.38	0.39		130	120*	
		——% S——			——mg Mn/kg——		
Drip management	Control	0.25	0.25	0.25	24	24	24
	Pulse	0.25	0.25	0.25	25	23	24
Average		0.25	0.25		25	24	
					——mg Zn/kg——		
Drip management	Control				10.3	9.7	10.0
	Pulse				10.5	9.5	10.0
Average					10.4	9.6	

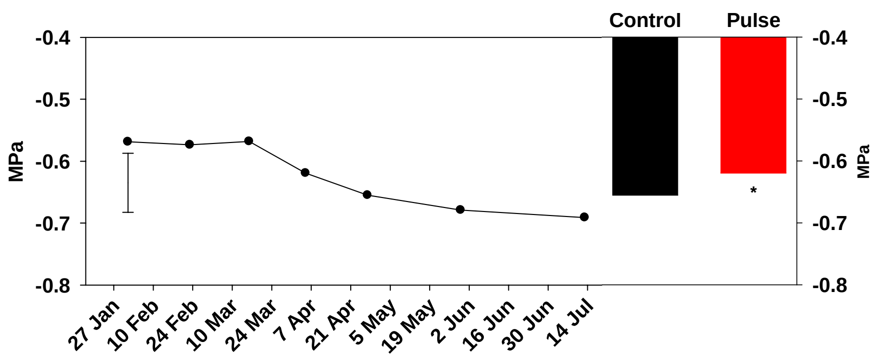
Tree water status

Midday stem water potential was measured from late January 2011 to the end of June 2011. Measurements were conducted immediately prior to irrigating the two conventional irrigation treatments. Trees in these two treatments were considered to be under the most water stress at this point.

Results are displayed in **Figure 18**. Considering only those trees involved in the irrigation × fertilization trial, over the period that stem measurements were conducted, time was the strongest influence on stem water potential, with stem water potential decreasing (becoming more negative) over the course of the measurement period. The manner in which the drip system was managed (*i.e.* a single application every week or so versus daily pulsed irrigations) also exerted some influence (black and red bars). The strategy used to manage fertiliser supplies to those trees had no influence on stem water potential.

Figure 18 Effect of time and drip irrigation management on stem water potential of Atwood navel orange trees at Dareton

Vertical bar represents LSD at P=0.05, and asterisk indicated a significant difference between means at P=0.05.



Considering only those trees involved in the irrigation comparison (*i.e.* conventional drip versus daily pulse or daily continuous), again, time was the major influence on stem water potential, but irrigation management did not exert a significant influence (data not shown).

In spite of the responses noted above, across the board stem water potentials were above -1.0 MPa, considered as the threshold for well-irrigated trees, indicating that all of the treatments provided adequate water supply at all times.

Fruit yield

The influence of season on total fruit number per tree, and the number of fruit in the 48-88 size classes (most valuable fruit), is illustrated in **Figure 19**. There were highly significant differences between seasons, as is common in citrus, which demonstrate a clear tendency toward biennial bearing.

Across all seasons, irrigation strategy affected yield, as shown in **Figure 20**. Trees subjected to pulse drip irrigation had more total fruit per tree than control trees or trees that were continuously dripped. However, more than half of the fruit from trees that were pulse dripped were outside the economically important 48-88 count sizes, whereas the majority of fruit from trees receiving the other two irrigation treatments were found in those economically important size classes. It is not clear why this should be so, and certainly indicates a need for more research into fruit growth under different drip irrigation management approaches.

Figure 19 Effect of season on total fruits per tree and fruit in the 48-88 size counts.

Red bars represent total fruits/tree and pink bars represent fruit in the 48-88 size counts. Different letters above columns indicate significant (P=0.05) differences between means within each comparison.

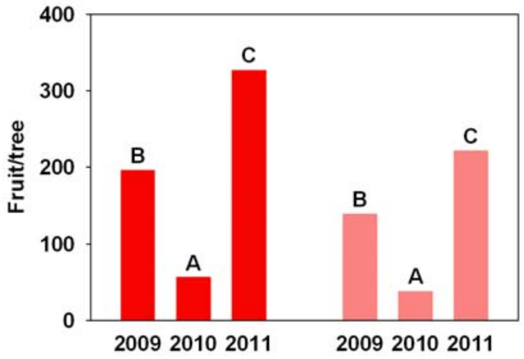
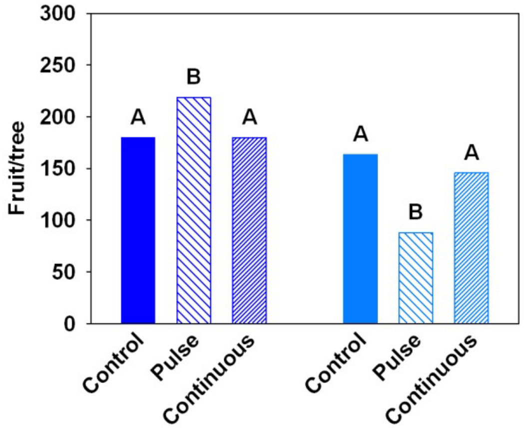


Figure 20 Irrigation effects on total fruits per tree and fruits in the 48-88 count sizes

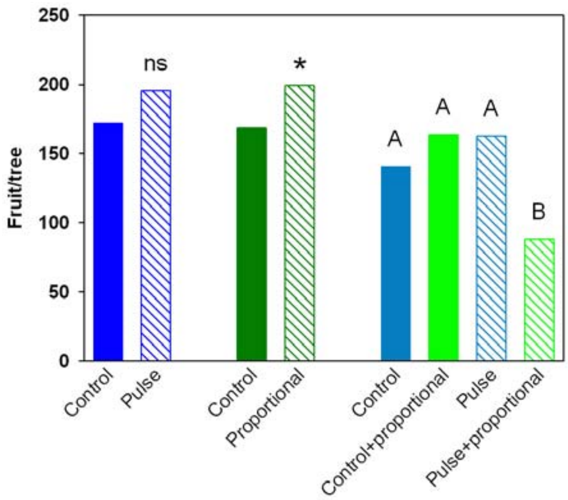
Dark blue bars represent total fruits/tree, and light blue bars represent fruit in the 48-88 size counts. Different letters above columns indicate significant (P=0.05) differences between means within each comparison.



Analysis of data from the trees involved in the interaction trial [*viz*. irrigation (control *vs*. pulse) × fertigation (control *vs*. proportional)] indicated that the total number of fruit per tree were unaffected by irrigation management, but that there were more fruit per tree if the trees had been supplied with fertiliser on a regular basis (Figure 21). The analysis also indicated that the number of fruit per tree in the 48-88 count sizes was lower if the trees had been pulse irrigated and received regular applications of fertiliser *via* the drip system. However, there was no clear indication whether this effect was due to a greater proportion of fruit not attaining a suitable size or too many fruit exceeding the 48 count size. Because fruit size distribution is critical to citrus producers' returns, this observation warrants further investigation.

Figure 21 Irrigation and fertigation main effects on total fruit per tree and interactive effects of irrigation × fertigation on fruit in the 48-88 size counts

Dark blue and dark green bars represent total fruit per tree and light blue and light green bars represent fruit in the 48-88 count sizes. Different letters above columns indicate significant (P=0.05) differences between means within each comparison.



Other observations

A number of other practical observations were made during the course of this trial. These observations relate to water distribution, installation of tensiometers and aspects of running drip irrigation/fertigation systems. Though empirical in nature, these observations warrant reporting here because the underpinning issues may qualitatively affect the efficiency of drip irrigation/fertigation systems.

Variability in soil moisture distribution became apparent during the trial, and may have contributed to the discontinuous records for each ceramic sampler referred to earlier. Shallow soil excavations occasionally indicated non-uniform wetting patterns beneath drippers (**Figure 22**). Tensiometers unwittingly placed in dry soil may result in over irrigation, and tensiometers placed in the wet soil may give an overly optimistic picture of the soil moisture status. In addition, concentration of applied nutrient solution into a smaller volume of soil will lead to deeper penetration, resulting in increased leaching.

Figure 22 Water movement beneath an emitter

The position of the emitter and 30 cm directly below the emitter are indicated. The soil 30 cm directly below the emitter and to the left was dry, but soil to the right was moist.

Excavations also indicated non-uniform colonisation of the rootzone by tree roots (**Figure 23**) Roots tended to clump in regions throughout the root zone, with considerable gaps between clumps. Again, root distribution in relation to tensiometer positioning may be a source of variability in assessments of soil moisture status provided by different sets of tensiometers, and may also reduce the efficiency of nutrient uptake.

Figure 23 Clumps of citrange roots in the Atwood navel orange trial at Dareton

As discussed in detail above, considerable variability in the volumes of soil solution extracted and in the composition of that solution was apparent (**Figure 13**). Installation of the ceramic cup sampling devices was identified as one contributing cause. Originally, the cups were placed in 80 mm diameter holes. Soil was then backfilled into the hole and compressed with a narrow dowel around the ceramic tip. The ability of the tubes to extract soil water was very poor with this method. The cups were removed and it was noticed that some ceramic tips were unstained (**Figure 24**). A tip that has very good contact with soil is normally stained brown and a white tip suggests that good contact with soil was not established during installation.

The sampling devices were re-installed by firstly placing loose soil in the 80 mm holes and then moderately compressing that soil with a large dowell. The ceramic tips were then pushed into this soil. This provided a much better contact between the soil and the ceramic tip, and resulted in more reliable volumes of soil solutions being extracted.

Figure 24 Ceramic cup sampling devices removed from soil in the Atwood navel orange irrigation/fertiliser management trial at Dareton

The left hand ceramic sampler is stained brown indicating good contact with the soil. The right hand ceramic sampler shows very little staining suggesting poor contact with the soil.

It should be noted, however, that the correct installation procedure for both tensiometers and solution samplers is to install into undisturbed soil, and bore the last few inches of the hole with a tool of the same or slightly smaller size than the tip of the device. The device should then be pushed into the hole, without any twisting, so that the tip makes very tight contact with the soil, maximising the potential for solution entry, and minimising disturbance of solution movement through the soil.

The level of management skill and input needed to run the conventional versus daily fertigation is much different. It was a relatively simple task to plan the conventional fertigation program, but planning and delivering mineral nutrients to the plots fertigated daily required almost daily adjustment of the amounts to be injected based on predictions of the amounts of water to be supplied as well more detailed knowledge of the solubility and compatibility of the various sources of mineral nutrients used. An additional complication arose when significant rainfall occurred that negated the need for irrigation, but in so doing prevented fertigation on those days. The development of 2 MS-Excel-based spreadsheets (described later) to make the planning of fertiliser programs and the estimation of irrigation needs easier was a direct response to the recognition of these difficulties.

Discussion

Bearing in mind that only two seasons' data have been reported, and that the trees are still relatively young, it is significant that there appears to be no advantage in high frequency drip irrigation and fertigation management over best practice conventional drip irrigation and fertiliser management, in terms of water savings, tree health or productivity. All of the combinations of irrigation and fertigation management delivered on a key requirement of any fertiliser application system; namely, maintaining adequate levels of most nutrients in the trees. This is similar to the conclusion reached by Syvertsen and Jifon, 2001 using similar aged 'Hamlin' orange trees growing on Swingle citrumelo roots in 7.6 m^3 lysimeter tanks. The lack of evidence supporting high frequency drip irrigation and fertigation management in citrus was recently identified in a comprehensive review by Carr (2012). Whether the lack of an effect is maintained as the trees grow larger and the roots need to service a larger leaf volume remains to be seen. The trial will continue through to the end of the 2012-13 season as part of HAL project CT07041.

Across the 2 irrigation seasons reported here, the daily dripped plots were supplied with about 40% more water than the conventionally dripped plots. A number of factors probably contributed to this result. Firstly, it was much simpler to accommodate predictions of significant rain into the irrigation schedule for the conventionally dripped plots than it was for the daily dripped plots. The conventionally dripped plots were therefore better able to utilise significant rainfall. The likelihood of significant rainfall was not easily accommodated into the schedule for the daily dripped plots because of the uncertainty of when rain may fall in a 24 hour period whilst aiming to maintain soil water at or near field capacity most of the time in those plots mindful of the much smaller volumes of soil being wet.

Secondly, there is some error associated with predicting water needs in the daily dripped plots when trying to maintain soil water at or near field capacity most of the time. Erring on the side of caution introduces a slight overestimation of water needs which, on a daily basis, is relatively small, but summed across a season may be significant

Thirdly, predictive and historical ET_o/water use from autumn through to spring closely matched actual water use for the drip pulse and conventionally dripped plots. But when ET_o was greater than 6 mm/day (*i.e.* during hot windy weather) the tensiometers indicated that soil water in the pulse plots was being depleted at a faster rate than predicted by ET_o. It is possible that evaporation from the soil surface is exacerbated under hot windy conditions with this form of drip irrigation. Providing 10-12% more water to the pulse irrigated plots when ET_o was predicted to be greater than 6 mm/day brought the tensiometer readings more closely in line with what would be predicted by ET_o, but also contributed to the higher amount of water supplied to these plots versus the conventional plots.

The variability in the soil solution data highlights the care needed when interpreting soil solution data. Fertigation management should not be based on one or two samples only, or on high or low readings at one sampling event. Large numbers of samples and analysis of trends over time are required to draw clear conclusions about the actual concentrations of nutrients in the soil solution.

Useful correlations between EC and NO_3^- have been noted in some studies based on soil cores (*e.g.* Das *et al.*, 1999). EC measurements can be conducted by time-domain reflectometry probes, which also estimate soil moisture content. In addition, EC measurements on soil solutions (extracted using ceramic cups or otherwise) is also much simpler and less expensive than measuring NO_3^- concentrations in the same solution. So it is tempting to argue that EC could be a reasonable indicator of NO_3^- concentrations in the soil solution. However, under the circumstances of this trial, EC did not correlate well with soil solution NO_3^-, and EC is, therefore, a poor surrogate measurement for nitrate. Other studies (*e.g.* Jiménez *et al.*, 2012) — also based on soil solutions extracted using ceramic cups — support this conclusion. It is possible that the relationship between EC and NO_3^- becomes less obvious as the concentrations of other anions such as phosphate and sulphate are manipulated independently of NO_3^-. Thus, reliance on EC as an indicator of soil solution NO_3^- in a dynamic fertigation regime is unlikely to be a useful management tool.

The detection of gradual N movement down the profile despite tight control of irrigation through the use of soil moisture monitoring, appropriate crop factors, and the incorporation of weather predictions in the estimate of the trees' water needs, suggests that maintaining N in the rootzone will always be a challenge. However, it appeared that N provided in a few large doses was even more prone to leaching, whereas N supplied in frequent small doses appeared to be less prone to leaching. Further, the conventional fertigation program used a urea and ammonium nitrate mixture, and in the light textured soils used for citrus production, both the urea and the nitrate would be prone to leaching.

The adoption of modern fertigation approaches often requires considerable investment in equipment. This trial is a unique opportunity to compare and demonstrate the impact of contrasting approaches to irrigating and fertilising young navel orange trees. No advantage was attributable to using more intensive approaches to irrigating and fertilising young citrus trees over a "best-practice" approach. As such, the trial will continue to act as a valuable resource for irrigators considering adopting fertigation: the information and experience gained will assist irrigators making decisions regarding investment in equipment and how to use that equipment.

Quantifying water and nutrient escape below citrus roots

Tools to help irrigators manage water and nitrogen in the rootzone

Summary

Advanced fertigation describes a range of management approaches to nutrient and water management of irrigated crops, all of which focus on optimising water and nutrient applications for immediate and complete satisfaction of crop requirements. Although advanced fertigation can lead to improved efficiency of water and nutrient use, the maintenance of high levels of water and nutrient in the rootzone make it particularly prone to significant drainage and leaching losses if management is imperfect.

Two trials were conducted to evaluate water and nutrient movement under advanced fertigation of citrus. One trial was conducted in weighing lysimeters at Loxton, South Australia, and the other in a citrus orchard at Dareton, New South Wales. At both sites monitoring incorporated SoluSamplers® to collect soil solution, allowing monitoring of soil solute movement through and beyond the rootzone.

In the lysimeter trial at Loxton even the lowest irrigation treatment (50% of ET_C replacement) produced significant drainage volumes, primarily due to high rainfall during the trial, including a single event of 51.8 mm. This rainfall event was clearly represented in lysimeter weight data, as well as soil water content data. The soil water content data clearly showed the rapid downward movement of water through soil layers within the lysimeters.

Soil water tension data from the lower levels of the lysimeters indicated that free drainage was not occurring at the base of the lysimeters, and highlighted the limitations of a simple gravitational drainage system in lysimeter installations.

The field site at Dareton was monitored for 2 full growing seasons, and produced an excellent set of soil solution data, including EC and NO_3^- concentration, at 4 depths within and beyond the rootzone. Leaching of nitrate was clearly demonstrated at certain periods during the growing season, during the peak of irrigation and fertigation applications, demonstrating the dangers inherent in less than ideal management of advanced fertigation.

Data from the lysimeter trial was used as inputs into a 2D/3D water and solute movement model (“Hydrus”), allowing calibration of the model with field measurements. Following calibration, good agreement was found between model simulations and measured data.

The model was then used to run a number of scenarios. The scenarios evaluated nitrate movement under different fertigation application patterns, involving pulsed and non-pulsed irrigation, and variable timing of fertigation applications across the daily irrigation pattern.

Results from the scenarios indicated that application of fertigation in the early or middle irrigation pulses for the day resulted in reduced efficiency of nitrate uptake, and greater leaching losses than application of fertigation in the later irrigation pulses, or at a low level across the whole day.

Introduction

“Advanced Fertigation” (AF) is a broad description given to an emerging group of intensive fertigation management systems developed over the last two decades to increase yield and quality of many permanent horticultural crops. Each AF system is different due to factors including climate, soil, water quality and level of management input. Fertigation can be defined as the application of fertilizers dissolved in irrigation water, and potentially allows water and nutrients to be placed in the zone of greatest root activity, potentially enabling rapid utilization by plants (Bar-Yosef, 1999). The overall aim of AF is to develop an irrigation and nutrition management program that increases yield and fruit quality, where the fundamental principle is that nutrients are applied regularly to a smaller volume of soil at a low application rate and at a high frequency to meet crop demand (Falivene, 2005).

"Open Hydroponics" (OH) is a variant of AF, and gets its name from the principles adopted from soil-less hydroponics for field based production. Professor Rafael Martinez-Valero from the University Miguel Hernandez in Spain brought together the concepts of OH in the early nineteen nineties. OH was originally developed as a management system to maximise citrus production on low fertility gravel based soils with poor quality water (Martinez-Valero and Fernandez, 2004). The system was commercialised as Martinez Open Hydroponics Technology (MOHT) (Falivene, 2005).

One of the claims made in support of AF is that by achieving a small, concentrated, confined root system, the crop's entire water and nutrient needs can be easily met and controlled through all stages of the production cycle (Edwards[6] - pers. comm.). Soil fertility is not considered important, and the soil is regarded as a medium to anchor the plant and accommodate the root system. It is claimed that even calcareous and saline soils can be utilised to grow citrus under AF as long as the soil is well drained (Edwards - pers. comm.). Ionic balance is an important consideration when formulating a nutrient mixture for application to orchards, and will help in preventing soil acidification (Martinez-Valero and Fernandez, 2004).

Nitrogen is the key limiting nutrient for citrus, and is therefore the main fertilizer input for citrus production. Nitrate is the final form of transformation from both organic and inorganic sources (Hillel, 2004). Mineral fertilizers are the main sources of NO_3^- for citrus production. Nitrate is removed from the soil by plants or decomposed by micro-organisms in the process of denitrification. In well aerated soils, denitrification is often negligible because of a lack of favourable conditions (Alva *et al.*, 2006). Nitrate, an anion, moves freely in soil water in mineral soils and hence has the potential to leach into the groundwater and waterways if soil water tensions exceed field capacity and fertigation is not well timed (Paramasivam *et al.*, 2002; Gardenas *et al.*, 2005; White, 2006).

Li *et al.*, 2004) found that a strategy of first applying water for one fourth of the total irrigation time, then applying fertilizer solution for one half of the total irrigation time, followed by applying water for the remaining one fourth of the total irrigation time left most NO_3^- close to the source and therefore optimized nutrient use efficiency.

High nitrate concentrations in groundwater are hazardous for two reasons. Firstly, the NO_3^- content of groundwater used for drinking purposes needs to be below 10 mg NO_3^--N L^{-1} (NHMRC and NRMMC, 2004). Concentrations higher than this have been linked to blue baby syndrome in infants. Secondly, high levels of leached NO_3^- can lead to eutrophication of surface water bodies where the groundwater discharges.

There are several techniques that can be used to estimate NO_3^- leaching. The most precise measurement technique uses lysimeters to measure actual volumes of drainage and NO_3^- concentration of the drainage water. A study by Syvertsen and Smith, 1995) used lysimeter-grown citrus trees fertilized at three N rates. The N concentration in the drainage water increased with N application rate and exceeded 10 mg L^{-1} for trees receiving the highest rate.

[6] Arthur Edwards, AgriExchange Pty. Ltd., Chowla Street, Renmark West, South Australia

However, lysimeters are expensive to install and during the installation cause considerable soil disturbance and therefore the soil in the lysimeter is often different to the surrounding intact soil. As such, lysimeter results must be verified with field data.

Computer based models can also be used to estimate deep drainage and NO_3^- leaching. There are several models capable of simulating unsaturated water flow, with each model having its own advantages. Models such as HYDRUS-2D and LEACHM use the Richards' equation to simulate water flux through a porous medium (Richards, 1931). Paramasivam *et al*. (2002) used a combination of water balance and modelling using the LEACHM model to estimate NO_3^- leaching and deep drainage in Florida, USA. It was found that 21-36% of the fertilizer N applied leached below the root zone in a sandy Entisol, whereas citrus tree uptake accounted for only 40-53% across all N treatments used in the study (112-448 kg ha^{-1} yr^{-1}).

Nitrate leaching has been estimated by determining a flux below the root zone using tensiometers and ceramic soil water extractors to measure NO_3^- concentrations. (Paramasivam *et al*., 2002) reported that NO_3-N leaching losses below the root zone increased with increasing N application (112 – 280 kg N ha^{-1} yr^{-1}) and the amount of water drained, accounting for 1-16 % of applied fertilizer N. They also reported that the NO_3-N at the bottom of the root zone stayed below 10 mg L^{-1} for most of the testing period.

The original objective of the project reported herein was to develop guidelines, practical grower-friendly tools and information packages and provide training for irrigators and support industry for the sustainable and economical use of the new fertigation technologies in citrus production. This was to be achieved through a number of sub-objectives. Those addressed in this component of the project were:

- to developing a framework to quantify water and nutrient escape below the rootzone of citrus trees growing in lysimeters and
- to calibrate a 2D/3D solute transport model under lysimeters and validate under field conditions to predict nutrient and water flux beyond the rootzone.

Two field investigations were carried out in order to address these objectives, a short term (2 week) trial in a set of weighing lysimeters at Loxton Research Centre, Loxton, South Australia, and a long term (2 year) field trial carried out at Dareton Primary Industries Institute, Dareton, New South Wales.

The results of these field investigations were used to calibrate and test HYDRUS modelling. The Loxton lysimeter data was used to calibrate a 2D HYDRUS model of water uptake and drainage and nutrient uptake and leaching, which was then tested against the field data from the Dareton site.

Results from both field investigations and the resultant modelling are reported herein.

Materials and methods

Loxton lysimeter site setup

Eight (8) above-ground weighing lysimeters were built and installed at Loxton Research Centre, Loxton, South Australia. Each lysimeter consisted of a large pot (1.03 m diameter × 1.20 m tall) made by cutting the top off a small rainwater tank. These pots sat on 1.2 × 1.2 m pallet scales fitted with 4 x 1 tonne load-cells, and connected to a computerised logging system which logged weight hourly.

Agricultural drainage pipe covered in a drainage sock was installed in the bottom of each pot as shown in **Figure 25**. A layer of approximately 250 mm of coarse washed river sand was added, which covered the drainage pipe, and a geo-textile material was placed over the top of the sand layer.

Figure 25 Drainage pipe and filter sock in bottom of lysimeter

Eight (8) healthy, uniform, young (~3 y-o) navel orange trees were excavated from a trial planting at Loxton Research Centre, and transplanted into the pots on September 2 2009 (**Figure 26**). Approximately 850 mm of soil depth was transferred to the pots with the trees, resulting in a final soil surface around 100 mm below the rim of the pot. The pots spent 2 months in a shade-house recovering from transplanting shock; there was a significant decline in tree health initially.

Figure 26 Transplanting a navel orange trees into lysimeters

The lysimeters were installed in an orange orchard on Loxton Research Centre, amongst existing trees, and the pots placed onto the scales in early December 2009 (**Figure 27** and **Figure 28**). Drainage water was directed through flexible piping into large bins installed below ground level between the rows of lysimeters (**Figure 29**).

Figure 27 Lysimeter field site

Each lysimeter had four soil solution sampling devices (SoluSampler®) installed at depths of 20, 40, 60 and 80 cm. The SoluSamplers® were installed at each of the four major compass points, to avoid interference.

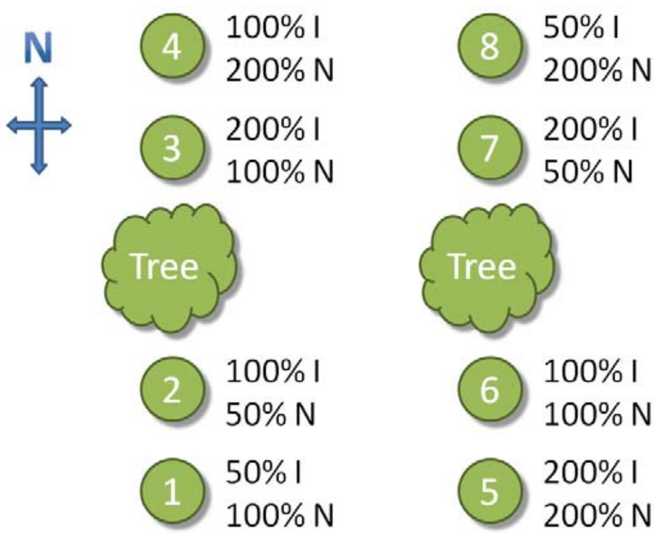


Figure 28 Layout of lysimeters in the field

Figure 29 Lysimeter drainage collection apparatus

Sentek® EnviroScan® capacitance soil water probes were installed in 4 of the lysimeters, with sensors at depths of 10, 20, 40, 60 and 80 cm. The sensors measured volumetric soil water content, and after the trial was completed were calibrated to gravimetric soil water content by excavating soil samples at the relevant depths.

UMS® T4®logging tensiometers were installed in the same four lysimeters, at depths of 65 and 80 cm, to measure soil water tension at the base of the pots, to assist in calculating drainage flux.

A diagrammatic representation of the instrumentation installed in the lysimeters is presented in **Figure 30**.

Loxton lysimeter experimental procedure

A matrix of irrigation and nutrient treatments were applied to the 8 lysimeters, as detailed in **Table 23**. Following a trial run in March 2010, irrigation treatments commenced on August 16 2010, and were fine tuned on August 24 2010. Nitrogen treatments were introduced on August 30, and ran for 2 weeks, until September 10.

Irrigation treatments were applied as 4 or 5 short irrigations per day, applied by an automatic irrigation controller. When nitrogen treatments commenced, one irrigation event per weekday was dropped from the controller, and instead was applied by hand watering with the appropriate volume of water containing the daily nitrogen dose. Nitrogen was applied as potassium nitrate (KNO_3), in which 10% of the nitrogen was present as the isotope ^{15}N.

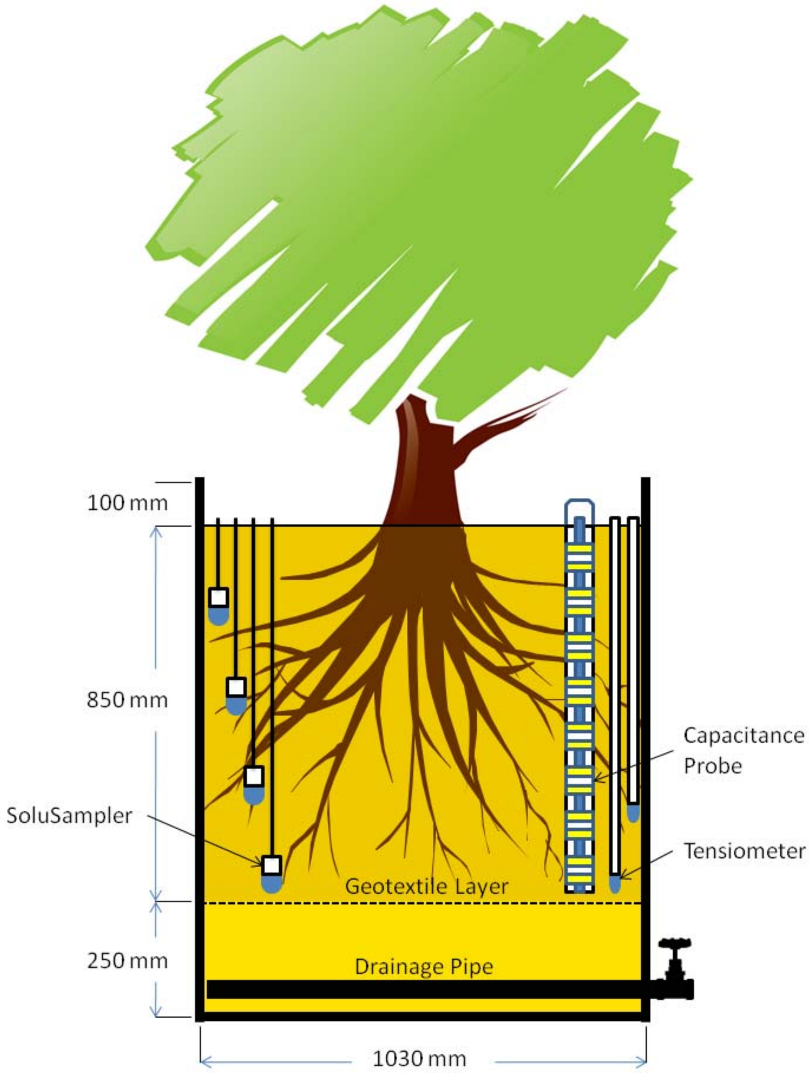


Figure 30 Diagrammatic representation of instrumentation within each lysimeter

Irrigation volume, rainfall and KNO_3 applied to each lysimeter were recorded throughout the trial. Lysimeter weight, soil water content and soil water tension were logged throughout, as was soil temperature at different distances from the pot wall in another identical pot on site.

Table 23 Treatments applied to each lysimeter

Nitrogen (% of industry practice)	Irrigation (% of estimated ET_0)		
	50	**100**	**200**
	Lysimeter number		
50	-	2	7
100	1	6	3
200	8	4	5

Leaves were sampled from each trial tree before the trial (August. 27), on the last day of treatment (September 10), and 2 weeks later (September 27), for determination of total N and ^{15}N mass spectrometry. Soil solution was sampled every week day at the same time, the volume of solute recorded, and the solute kept for analysis. Drainage volume was measured 3 times per week, and samples collected for analysis.

Daily inputs of irrigation, rainfall and KNO_3 to each lysimeter are presented in **Table 24**. Irrigation inputs were reduced on August 24 2010, because large drainage volumes were being generated even by the 50% irrigation treatment. Potassium nitrate supply commenced on August 8 2010, and occurred every week day for the next 2 weeks.

Table 24 Reference evapotranspiration, and rainfall, irrigation and potassium nitrate inputs by treatment during August and September 2010 at the Loxton lysimeter site

Date	ET_0 (mm)	Rain (mm)	Irrigation			Nitrogen		
			50%	100%	200%	50%	100%	200%
			L/pot			*g $KN0_3$/pot*		
16/8	1.68		3.0	6.0	12.0			
17/8	2.86	5.0	3.0	6.0	12.0			
18/8	3.26	3.0	3.0	6.0	12.0			
19/8	2.46		3.0	6.0	12.0			
20/8	1.99	0.4	3.0	6.0	12.0			
21/8	1.98		3.0	6.0	12.0			
22/8	2.79	0.4	3.0	6.0	12.0			
23/8	2.09	0.4	3.0	6.0	12.0			
24/8	2.46	0.6	2.4	4.2	8.4			
25/8	2.57	5.4	1.6	3.0	6.0			
26/8	2.16	0.2	1.6	3.0	6.0			
27/8	2.00	0.2	1.6	3.0	6.0			
28/8	1.14		1.6	3.0	6.0			
29/8	2.08		1.6	3.0	6.0			
30/8	3.16		1.7	3.0	6.0	7.2	14.4	28.8
31/8	2.89	0.2	1.5	3.0	6.0	7.2	14.4	28.8
1/9	2.17	0.4	1.5	3.0	6.0	7.2	14.4	28.8
2/9	1.98		1.5	3.0	6.0	7.2	14.4	28.8
3/9	2.97	51.8	1.5	3.0	6.0	7.2	14.4	28.8
4/9	1.91	1.0	1.4	3.0	6.0			
5/9	1.87	1.4	1.4	3.0	6.0			
6/9	2.09		1.5	3.0	6.0	7.2	14.4	28.8
7/9	2.48		1.5	3.0	6.0	7.2	14.4	28.8
8/9	2.06	1.4	1.5	3.0	6.0	7.2	14.4	28.8
9/9	3.43	0.2	1.5	3.0	6.0	7.2	14.4	28.8
10/9	2.85		1.5	3.0	6.0	7.2	14.4	28.8
11/9	1.40		1.4	3.0	6.0			
12/9	2.74		1.4	3.0	6.0			
Totals	**65.52**	**72.0**	**55.2**	**109.2**	**218.4**	**72.0**	**144.0**	**288.0**

Dareton field site setup

The field site was located on Dareton Primary Industries Institute, located in the Sunraysia irrigation of south west NSW. The climate is characterized as dry with warm to hot summers and mild winters. The average yearly rainfall is 280 mm with rainfall evenly distributed throughout the year. Potential evapotranspiration is high at 1400 mm per year.

The site was managed under an Advanced Fertigation System (AFS) regime, and contained a number of mandarin varieties on citrange rootstock. The monitoring site was established on October 10 2005. This site did not represent a controlled trial site, but rather demonstrated solute dynamics under a specific citrus orchard management regime.

The soils are alkaline (Class IIIA), with red sand to sandy loam topsoils overlaying a heavier sub-soil. The site has top soil and root zone depths of 1.05 m. The total organic carbon content of the soil is very low at 0.4% in the first 0.3 m and below 0.25% for the remainder of the rootzone. The site is irrigated with Murray River water which has salinity below 0.3 mS m^{-1}.

Table 25 Summary of pre-planting soil chemical analyses for the AFS site at Dareton

Depth interval	Exchangeable Al	Ca	K	Mg	Na	ESP	EC 1:5
cm	*cmol(+) Kg^{-1}*					*%*	*dS m^{-1}*
0-30	0.1	7.1	1.3	1.5	0.1	0.99	0.13
30-60	0.1	8.7	0.72	2	0.24	2.04	0.15
60-90	0.1	9.7	0.5	2.4	0.46	3.5	0.29
	pH $CaCl_2$	**Total organic C**	**Total N**	**KCl-extractable NO_3^-**	**NH_4^+**	**Bray P**	**S**
		%		*mg Kg^{-1}*			
0-30	7.5	0.4	0.065	30	0.77	17	5.7
30-60	8.1	0.25	0.044	23	<0.3	5.6	12
60-90	8.2	0.22	0.044	39	<0.3	3.7	20

The pre-planting chemical and physical characteristics of the soil on the AFS site are set out in **Table 25** and **Table 26**. The soil contained a high amount of sand, with a loamy sand texture to 0.6 m and a loam texture below that.

Table 26 Summary of particle size analysis for the AFS site at Dareton

Depth interval	Clay (<2 µm)	Silt (2-20 µm)	Fine sand (20-200 µm)	Course sand (200-2000 µm)	Gravel (>2000 µm)	Texture
cm	*%*					
0-30	9	12	35	43	0	Loamy sand
	10	14	37	39	0	Loamy sand
30-60	10	14	35	41	0	Loamy sand
	10	14	34	42	0	Loamy sand
60-90	11	15	32	42	0	Loam
	12	17	35	37	0	Loam
90-120	14	20	27	39	0	Loam
	14	20	28	38	0	Loam
120-150	13	17	31	38	0.26	Loam
	13	17	31	38	0.26	Loam

The air to water permeability ratio (AWR) is an index of soil stability (Hutson, 1982). An AWR of 1 indicates a completely stable soil, whereas a value of 20 indicates approximately the instability threshold for most soils. **Table 27** indicates a general increase in AWR with depth. Particularly, the 0.5-0.6 m and 1.2-1.5 m depths had AWR close to and above the instability threshold. High AWR can be caused by swelling or dispersion, or a combination of the two. Dispersion is usually caused by high levels of exchangeable sodium and low concentrations of dissolved salts. **Table 25** indicates that the exchangeable sodium percentage (ESP) increased with depth and the soil salinity was low. This suggests a potential for water permeability to decrease deeper in the soil profile.

Figure 31 shows the soil moisture release curves for the AFS site, measured using the Tempe Pressure Cell method (Klute and Dirksen, 1986). The soil moisture release curve represents the relationship between volumetric water content (θ) and soil water pressure (h). Three large undisturbed soil cores were sampled from a depth of 1.0 m in the tree line half way between two trees. An undisturbed subsample core (2.75 cm radius and 3 cm height) was taken from the field core and used in the Tempe Pressure Cell. **Table 28** shows the θ at -1500 kPa soil water pressure was between 0.037 and 0.044 (cm^3 cm^{-3}) for the ten samples tested.

Table 27 Air to water permeability ratio down the AFS site soil profile

Depth interval	Air to water permeability ratio
cm	*cm^3 cm^{-3}*
0-20	9.2
20-30	12.4
50-60	19.4
100-120	13.3
120-150	29.8

Table 28 Volumetric water content at -1500 kPa soil water pressure

Sample Number	θ_v
	cm^3 cm^{-3}
1	0.044
2	0.042
3	0.037
4	0.042
5	0.044
6	0.044
7	0.042
8	0.041
9	0.038
10	0.040

The site was drip irrigated, and fertigated weekly. The site consisted of 3 rows of 104 m length, at a row spacing of 5.0 m and tree spacing of 2.0 m. The irrigation system consisted of double drip lines per tree row with 1.6 L/h emitters at 0.4 m spacing, giving an application rate of 1.6 mm/hr.

The AFS site fertigation injections always commenced two hours before the end of the irrigation event. The fertilizer took one and a half hours to inject, leaving half an hour for the lines to be flushed.

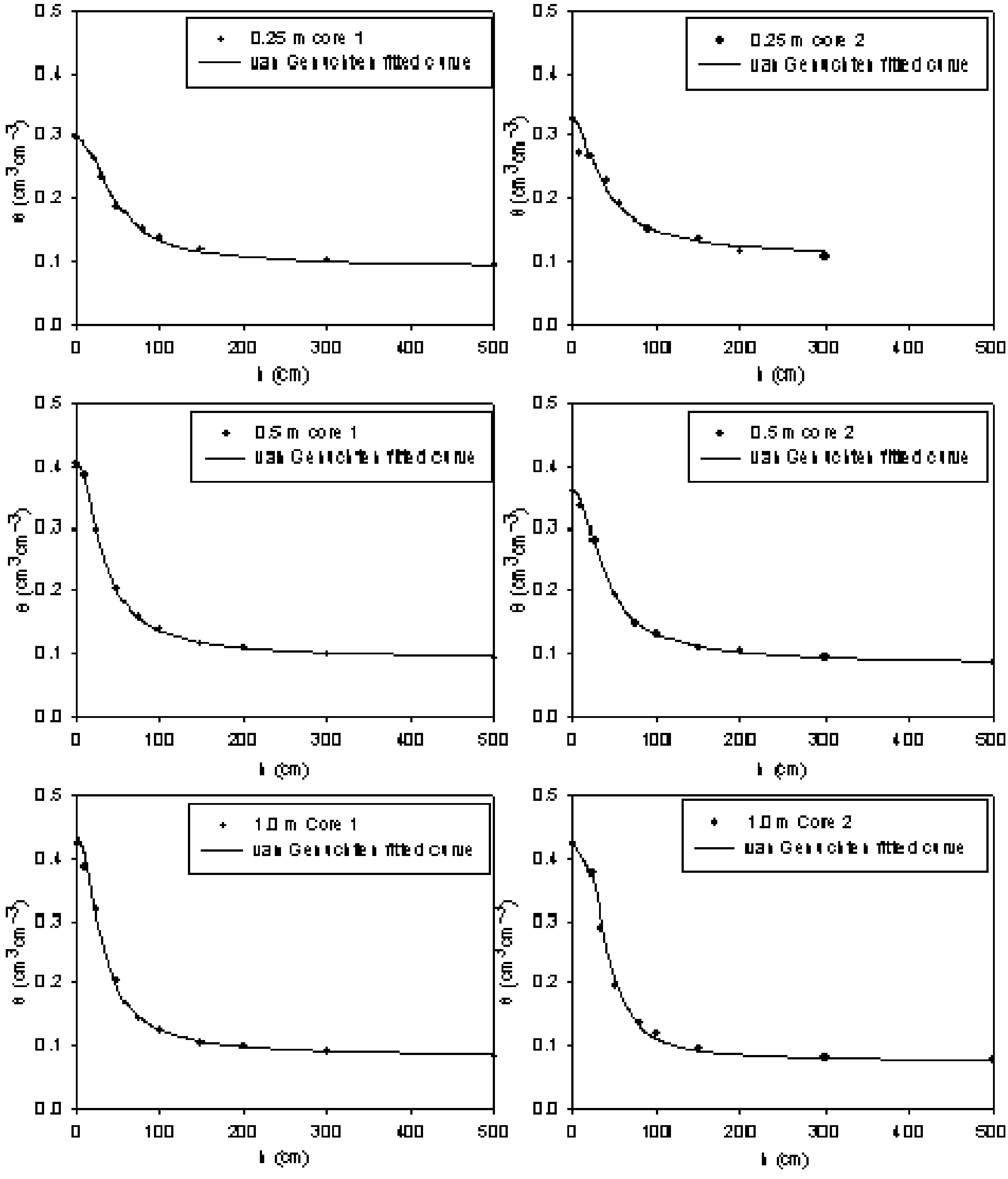


Figure 31 Soil moisture release curve for AFS site

Dareton experimental procedure

The Dareton field site was monitored for 2 seasons, between August 1 2006 and June 31 2008. The site was treated as one block, irrigated roughly every third day at peak, and fertigated weekly. Irrigation and rainfall, along with fertiliser applications, are shown in **Figure 32**.

Soil solutions was sampled once a week using SoluSamplers®, from 4 depths (25, 50, 100 and 150 cm) below the surface. The solution collected was analysed for electrical conductivity (EC) and NO_3^-.

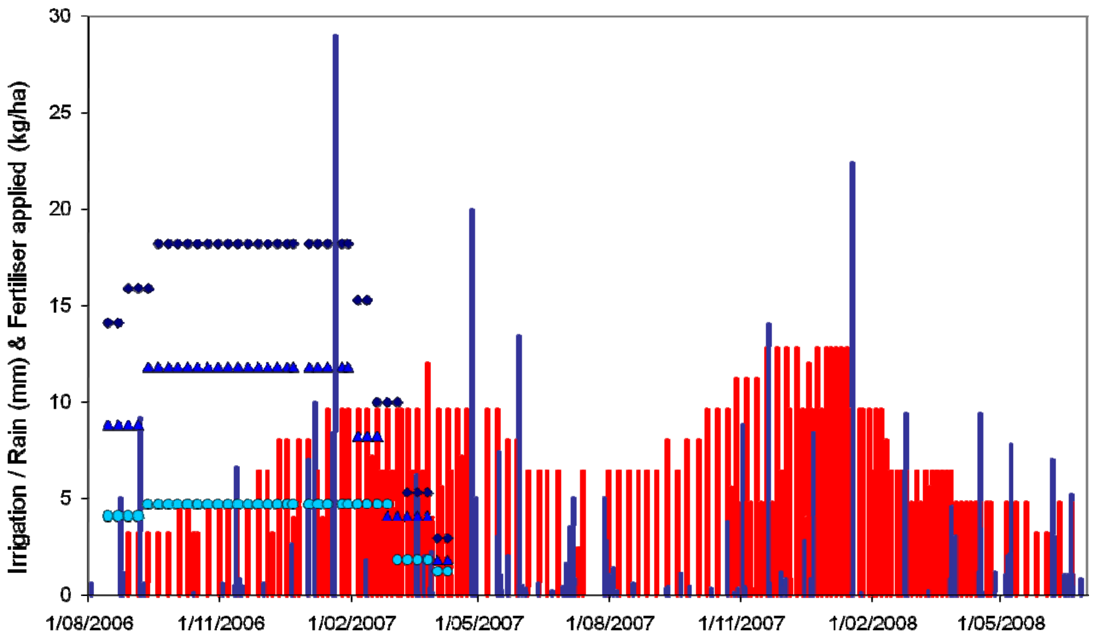


Figure 32 Irrigation, rainfall and fertiliser applications to Dareton AFS field site

■, irrigation; ■, rain, ♦, ammonium nitrate; ▲, potassium sulphate; ● tech. grade MAP

Modelling parameters

To date modelling has been carried out using data from the lysimeters at Loxton only. Further work utilising the field data from the Dareton site is ongoing.

Estimation of water transmission parameters

The particle size analysis and bulk density data from 0-20, 20-40, 40-60, 60-85 and 85-110 cm depths from all lysimeters was used to estimate the water transmission parameters, viz. θr, θs, Ks, α, n and l for all soil layers. The direct measurement of these parameters in the field or laboratory is time consuming and costly. Therefore, these parameters were estimated using ROSETTA (Schaap *et al.*, 2001), a pedotransfer function software package that uses a neural network model to predict hydraulic parameters from soil texture and related data. Inputting particle size analysis and bulk density data into ROSETTA resulted in water transmission parameters for different soil layers which were optimised during calibration of the model, and final values are shown in **Table 29**. The value of l was assumed to be 0.5, as recommended by Mualem, 1976).

Root distribution and water uptake functions

Roots are expected to grow further vertically than laterally in a closed system like a lysimeter, where lateral growth is constrained. Hence the orange root distribution in the lysimeters was described using the model published by Vrugt *et al.*, 2001), with most roots extending 50 cm laterally and 90 cm vertically. The following parameters were used in the model: $Zm = 90$ cm, $Z^* = 30$ cm, $Xm = 50$ cm, $X^* = 25$ cm, $px = 2.0$, $pz = 1.5$, where Xm and Zm are the maximum horizontal and vertical distance beyond which root density is zero; pz, px, Z^*, and X^* are empirical coefficients. The resultant root distribution evolved by the model is shown in **Figure 33**.

Table 29 Soil hydraulic (van Genuchten) parameters used in the model for the different irrigation treatments in the Loxton lysimeters

Depth interval	θr	θs	α	n	Ks
cm	$cm^3 cm^{-3}$		cm^{-1}		$cm\ hr^{-1}$
50% irrigation					
0-20	0.06	0.39	0.0274	1.92	6.75
20-40	0.06	0.36	0.0268	1.91	5.43
40-60	0.05	0.37	0.0308	1.99	9.92
60-85	0.05	0.34	0.03	1.85	4.3
85-110	0.03	0.4	0.095	2.68	29.7
100% irrigation					
0-20	0.06	0.37	0.0219	1.90	6.37
20-40	0.06	0.38	0.0175	1.81	5.01
40-60	0.05	0.35	0.0214	1.99	4.94
60-85	0.05	0.33	0.0291	1.85	4.2
85-110	0.03	0.4	0.095	2.68	29.7
200% irrigation					
0-20	0.06	0.38	0.0218	1.94	4.37
20-40	0.06	0.36	0.0178	1.81	4.52
40-60	0.05	0.36	0.0188	1.93	4.64
60-85	0.05	0.35	0.0209	1.85	3.8
85-110	0.03	0.4	0.095	2.68	29.7

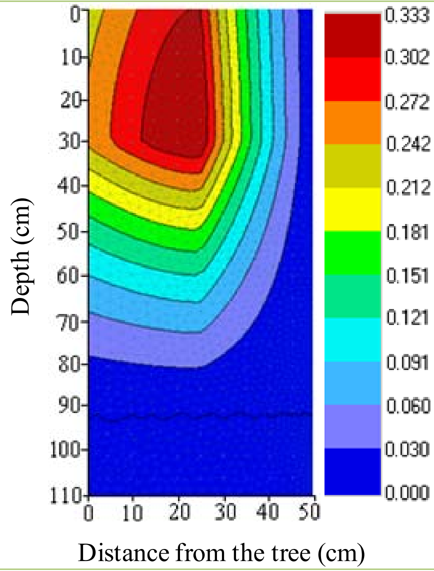
The following parameters of the Feddes *et al*., 1978) model were used: $h1 = -10$, $h2 = -25$, $h3max, = -500$, $h3min = -800$, $h4 = -8000$ cm; $r2, high = 0.5$ cm d^{-1}, and $r2, low = 0.1$ cm d^{-1}. The parameters $h1 - h4$ represent different pressure head values which affect root water uptake in the soil. Similar root distributions were used for all irrigation treatments because little information is available on the effect of a given volume of water on root distribution, although in reality the distributions may differ with water availability and inherent soil variations.

Initial and boundary conditions

The simulation domain was represented by a 110 cm deep and 50 cm wide cross section, with a line source of discharge at 25 cm from the tree butt rolled in a circular fashion. This resulted in two dimensional axis-symmetrical flow, representing the entire lysimeter as the transport domain for numerical simulations (**Figure 34**). The soil surface was subjected to atmosphere boundary condition with a variable flux imposed by line source of dripper discharge. The actual evaporation (Ea), actual transpiration (Ta), irrigation and rainfall were used to represent the atmospheric boundary condition. The sides perpendicular to the flow direction were no flow boundaries, and there was a seepage face (5 cm) at the bottom right boundary to drain the bottom flux. Solute transport concentration flux conditions were imposed as top and bottom boundary conditions. The initial soil water content distribution was based on the EnviroSCAN® measured values, which are shown in **Figure 35** for different irrigation application treatments. The boundary condition representing NO_3^- movement is a third-type Cauchy boundary condition that describes the NO_3^- movement during defined irrigation intervals.

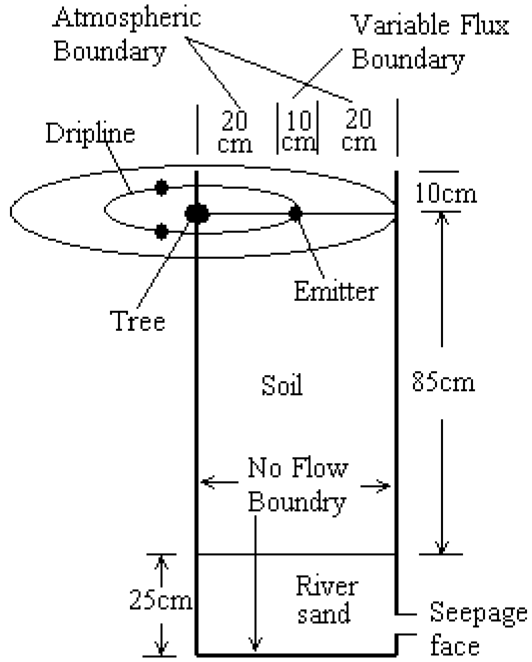
Figure 33 Predicted citrus root distribution in the Loxton lysimeters

Predictions based on model published by Vrugt *et al*., 2001).



Spatial distribution of NO_3^- in the transport domain was simulated using the convection–dispersion equation for a nonreactive tracer. Molecular diffusion was neglected as it was considered negligible relative to dispersion. Being a negatively charged ion, NO_3^- in the soil solution is not attracted to the negatively charged soil system. Hence, its adsorption on soil particles is negligible. Most citrus growing soils in Australia are coarse textured, with good drainage, high oxygen levels, low organic matter and low microbial populations, and, therefore, unfavourable for denitrification. Therefore, it was assumed in this study that NO_3^- is either taken up by the tree as a passive transport of ions, or moved downward with soil water. The initial NO_3^- concentration was assumed to be zero for all simulations.

Figure 34 Lysimeter experimental details and model domain showing boundary conditions



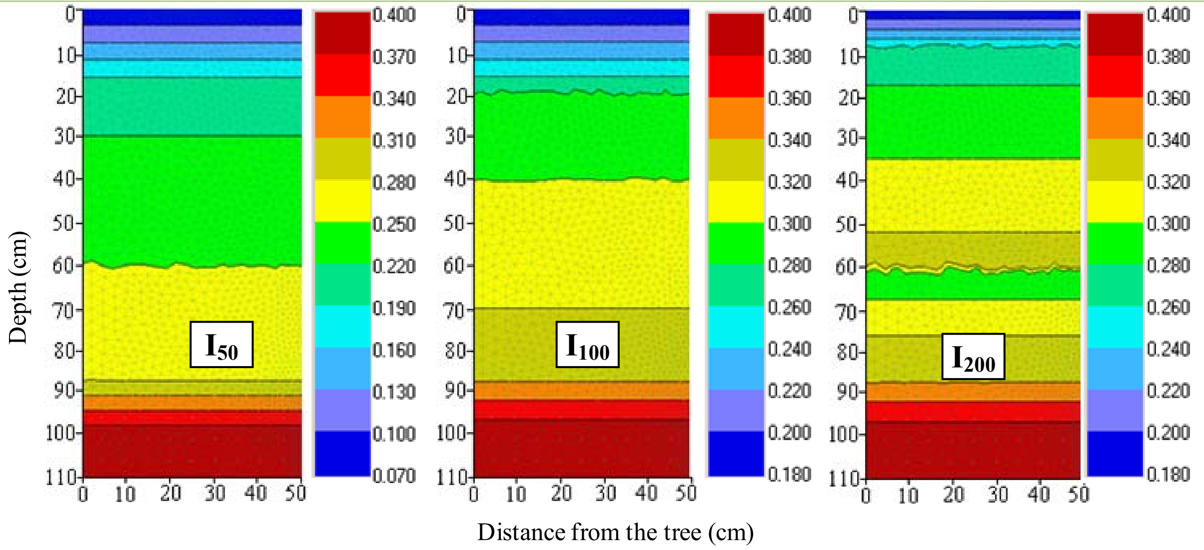


Figure 35 Initial volumetric soil moisture ($cm^3\ cm^{-3}$) distributions in indicated irrigation treatments

Longitudinal dispersivity was considered to be 5 cm, with the transverse dispersivity being one-tenth of the longitudinal dispersivity. Similar values of these parameters have been used in other studies (Gardenas *et al.*, 2005; Hanson *et al.*, 2006). The measured mean values of bulk density from different soil layers (1.6, 1.64, 1.69, 1.75 and 1.7 Mg m^{-3} from 0-20, 20-40, 40-60, 60-85 and 85-110 cm depth) averaged over all the treatments were utilised for the simulations.

Flow domain and simulations

Simulations for a 29 day period with hourly time interval were conducted. The transport domain was discretized into 3,294 finite elements, with a very fine grid around the dripper and near the seepage face (1 cm), and elements gradually increasing in size farther from these two locations (up to 4 cm). During irrigation, the drip line boundary had a constant water flux, *qo*. The constant water flux is equal to the water application rate over the modelled drip line surface area which was calculated as:

$$qo = \frac{4x3x1000x24}{(\pi r_2^2 - \pi r_1^2)} = 7.636 cmhr^{-1}$$

where r_1 and r_2 are the inner and outer radii of the circular dripline discharge boundary, assumed to be 20 and 30 cm, respectively. There were 3 pressure-compensated drippers on the dripline in each pot, each having a discharge rate of 4 L h^{-1}.

Fertigation scenarios

Keeping all the parameters the same, numerical simulations were conducted for the supply of dissolved nitrogen fertiliser at different times during an irrigation event and for different irrigation management strategies [*i.e.* 50, 100 and 200% of requirements, and pulse (5/day) and continuous drip]. In all scenarios, fertigation was assumed to start one day after the start of simulation. Fertigation was introduced in the same pattern as applied in the lysimeters, but the timing of the pulse was varied. The fertigation pulse occurred either at the beginning (PF_1), middle (PF_2) or end (PF_3) of a daily irrigation event. Because the daily irrigation event consisted of 5 pulses, the fertigation corresponded to the 2nd, 3rd and 4th pulse in PF_1, PF_2 and PF_3 respectively. In addition to these simulations, two continuous fertigation scenarios were also modelled. The first consisted of applying the same total amount of fertilizer as applied in single pulse fertigation, but applied continuously with all pulses (PF) except the last pulse for flushing. The second scenario consisted of continuous irrigation of the same duration as under pulsed treatments, with fertigation all the time (CF), except for the same period of flushing at the end of the irrigation application.

Statistical test

The root mean square error (*RMSE*) was calculated to compare the experimental and predicted values of soil water content and salinity as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Mi - Si)^2}$$

where, *Mi* and *Si* are measured and simulated values for an output variable, and *N* is the number of observations.

Results & discussion

Loxton lysimeters

Irrigation, rain and fertiliser application records are presented in **Table 24**. A major rainfall event of 51.8 mm was recorded on September 3 2010. This rain event had a significant impact on the treatments, as can be seen in some of the data sets to follow.

Table 30 Drainage volumes collected from the Loxton lysimeters during August and September 2010

	% Irrigation							
	50		100			200		
	% Nitrogen							
Date	100	200	50	100	200	50	100	200
	L/lysimeter							
13/8	8.6	10.5	21.0	18.8	19.7	44.7	12.1	43.7
16/8	6.9	7.1	16.1	15.1	10.4	34.1	25.3	34.7
18/8	3.6	4.3	10.2	9.9	10.2	23.4	20.8	23.5
20/8	5.2	7.8	12.0	11.8	12.1	22.1	22.1	22.9
23/8	5.0	6.1	14.0	12.3	13.2	30.1	28.2	32.3
25/8	1.7	4.1	8.3	8.9	8.1	17.3	17.1	19.2
27/8	0.0	3.5	7.6	8.7	7.0	12.7	13.1	15.0
30/8	0.0	3.9	8.7	7.8	10.0	14.8	14.7	17.4
1/9	0.0	2.0	4.8	6.6	4.3	8.5	8.6	10.6
3/9	0.0	1.1	3.3	5.1	3.1	7.6	7.2	9.1
6/9	0.0	41.1	50+	22.7	40.7	49.3	50.0	60+
8/9	0.0	3.5	6.1	8.5	7.5	4.8	10.5	12.1
10/9	0.0	1.9	4.4	6.5	5.3	0.9	9.0	10.8
13/9	0.0	1.7	5.2	8.9	5.4	4.5	12.5	14.7
Totals	**31.0**	**98.6**	**121.7**	**151.6**	**157.0**	**274.8**	**251.2**	**266.0**

Drainage volumes collected from each lysimeter are presented in **Table 30**. Significant drainage was collected from the 50% irrigation treatments, indicating that the volume of water applied to these lysimeters was more than the trees were using. Small tree size and shading from adjacent trees may have contributed to less water being used by the trees in the 50%

irrigation/100% N treatment. Drainage volumes from the remainder of the treatments were relatively consistent with the irrigation treatments applied.

Rainfall had a significant impact on drainage. The volume of drainage collected on August 6 was elevated in every treatment (**Table 30**), as a result of the 51.8 mm of rain on August 3. In addition, the total rainfall over the trial period was 72 mm, which resulted in each lysimeter receiving an additional 60 L.

Drainage water was sampled each time drainage volume was recorded, 3 times each week. Soil solution samples were collected daily, but only those collected on the day of a drainage sample were analysed.

Electrical conductivity of soil solution and drainage samples is shown in **Figure 36**. Conductivity was low initially, and rose at 20 cm in some treatments from around September 3. Rises at greater depth occurred later, as the applied fertiliser made its way down through the soil profile. Electrical conductivity of soil solutions extracted from 60 and 80 cm and of the drainage water from all lysimeters showed some increase in EC, although some of the responses were very minor.

The levels of nitrogen and ^{15}N in the water samples were extremely low, possibly due to very rapid uptake by the trees. As a result, the analytical results were at or below the limit of detection, and these data were not considered further.

Leaf N and ^{15}N concentration are shown in **Figure 37**, at different scales. Samples were taken before fertigation commenced (August 27), immediately after fertigation ceased (September 10), and 2 weeks after fertigation ceased (September 27). This last sampling was to allow for assimilation of nitrogen after the end of fertigation.

Assimilation of nitrogen continued after the end of fertigation, as indicated by the rise in ^{15}N levels in the leaves between September 10 and 27.

Weight changes in the lysimeters are shown in **Figure 38**. The absolute mass of each lysimeter is different, so the data have been adjusted to similar zero points. The weight changes are to scale, in kilograms. The most obvious feature of these graphs is the rainfall event overnight on September 3, which delivered a total of 51.8 mm (**Table 24**), and caused significant increases in lysimeter weights. Lysimeter weights returned to pre-rainfall levels over the course of around a week.

Soil water contents at different depths within the 4 lysimeters equipped with capacitance sensors (EnviroScan®) are shown in **Figure 39**. Again the impact of the large rainfall event on September 3 is very obvious. In all cases a response to the rainfall was evident all the way down to 80 cm, as the water from this rainfall event drained down through the rootzone.

Another significant feature of the soil moisture graphs is the high water content at 80 cm in all lysimeters, compared to other depths. The diurnal variations in water content suggest that there was root water uptake at all depths in all of the lysimeters. While it is possible that the root activity at 80 cm was less than at shallower depths, thus leading to higher water content, it is more likely that the passive drainage system employed in the lysimeters resulted in a zone of elevated water content just above the bottom of the lysimeters (Derby *et al.*, 2002; Kosugi and Katsuyama, 2004; Lewis and Sjostrom, 2010).

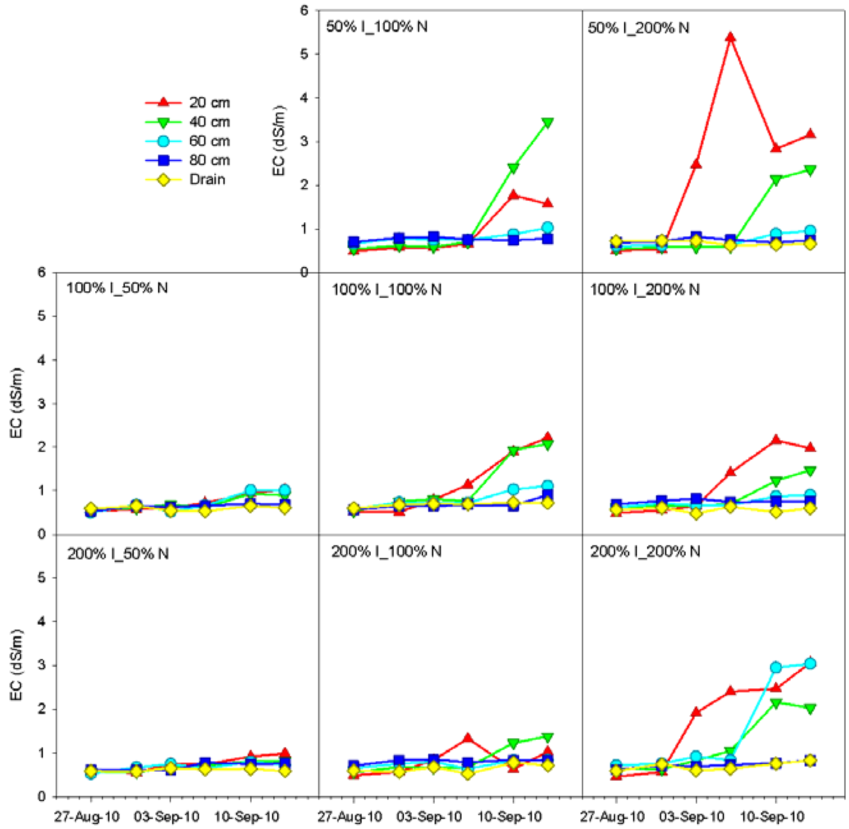


Figure 36 EC of drainage water collected and of soil solutions extracted from 4 depths from the Loxton lysimeters

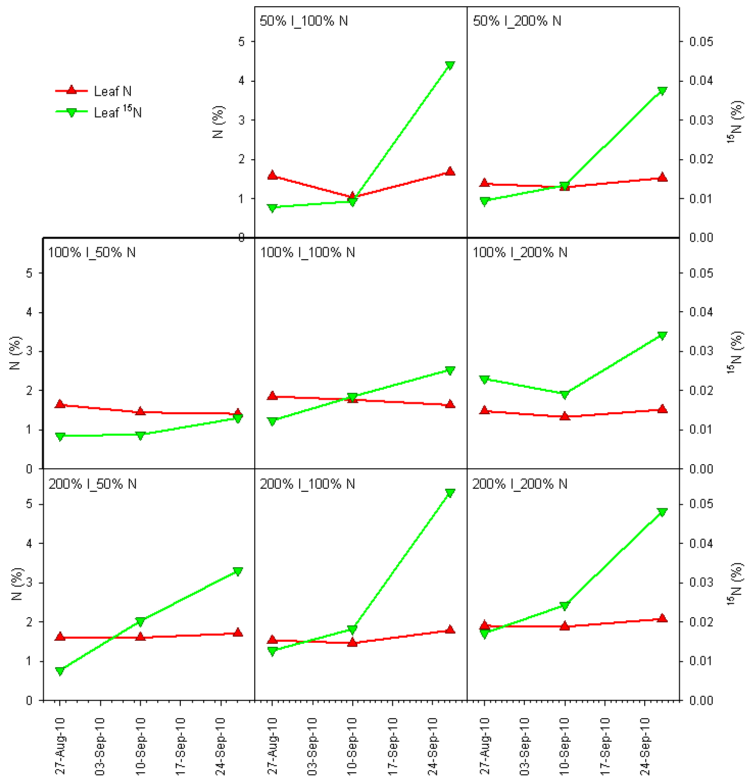


Figure 37 Leaf N and ^{15}N content

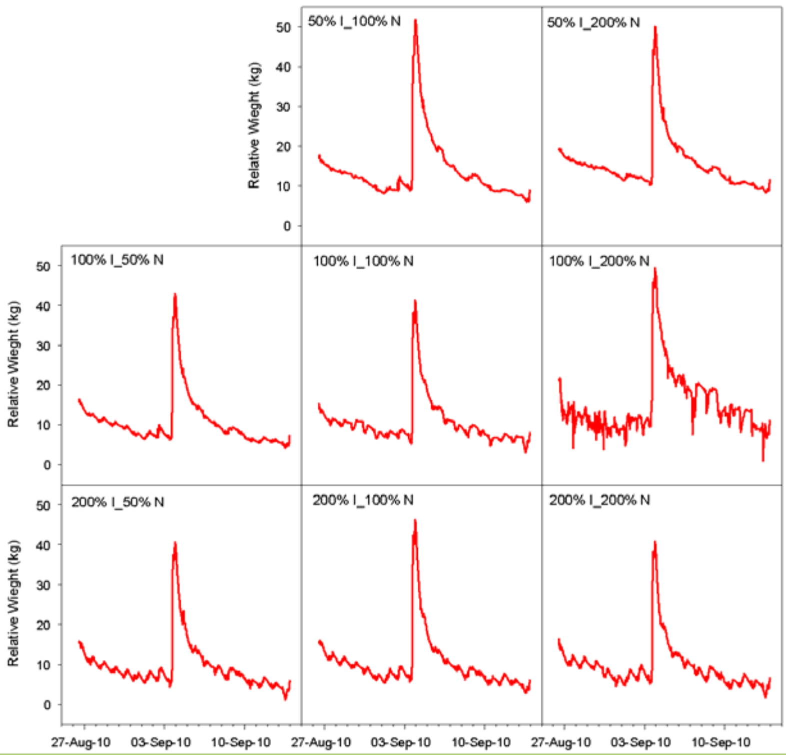


Figure 38 Relative weight changes in Loxton lysimeters

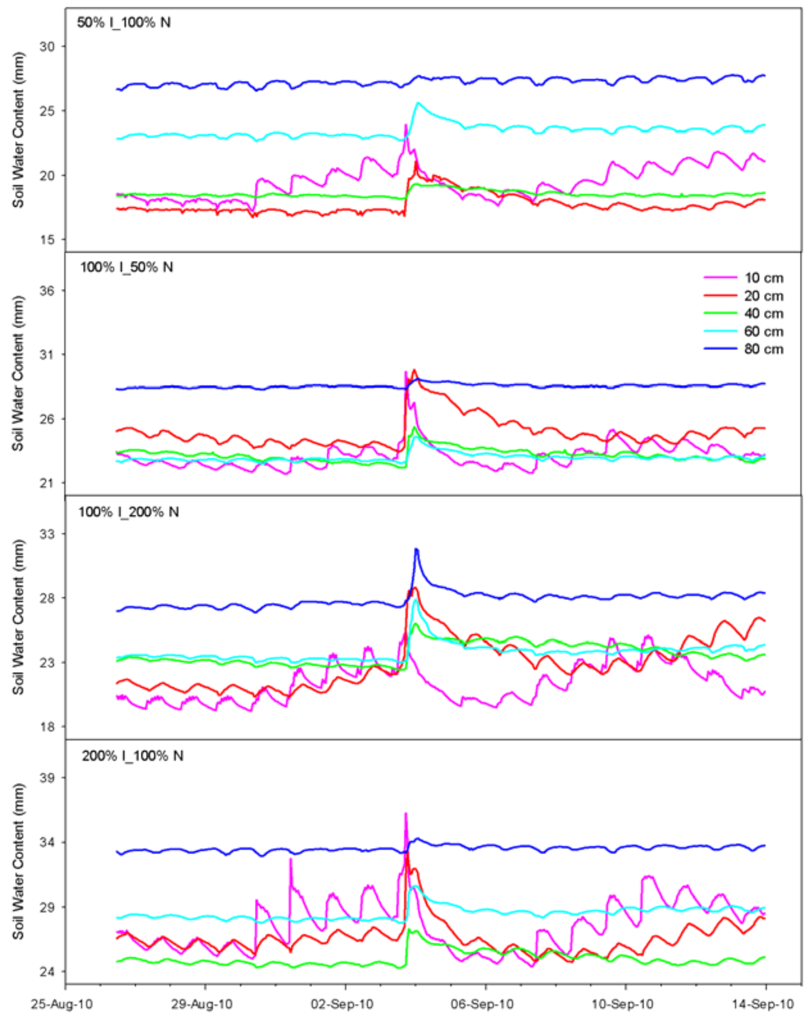


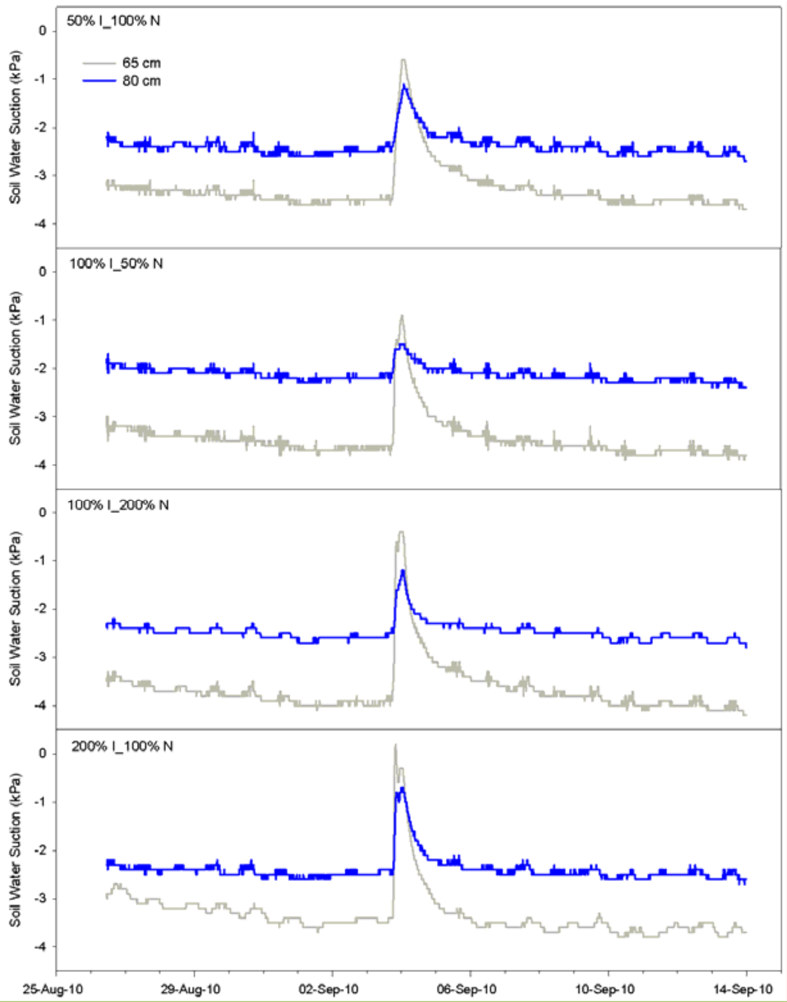
Figure 39 Soil water content measured with capacitance probes at 4 depths in Loxton lysimeters

Soil water tension at the bottom of the lysimeters, as measured with logging tensiometers (UMS® T4®) is shown in **Figure 40**. Again, the effect of the September 3 rainfall event is clearly apparent.

More significantly, the soil water tension at 80 cm was lower than at 60 cm (i.e. wetter) at all sites for the whole monitoring period, except for immediately following the rainfall event. This is in line with the data in **Figure 39**, but calculations of drainage flux using tensiometer data require the opposite condition (that is lower soil water tension at shallower depth), as is generally found in free draining situations (Hutchinson and Bond, 2001). This further supports the conclusion that the passive drainage system is resulting in a region of increased water content near the bottom of the lysimeters.

In addition, soil water tension at field capacity is generally agreed to lie somewhere between -8 and -10 kPa. The lowest soil water tension measured at 65 cm depth was around -4 kPa, and at 80 cm depth was around -2.5 kPa, indicating that these soils were well above field capacity.

Figure 40 Soil water tension measured with logging tensiometers at 2 depths in the Loxton lysimeters



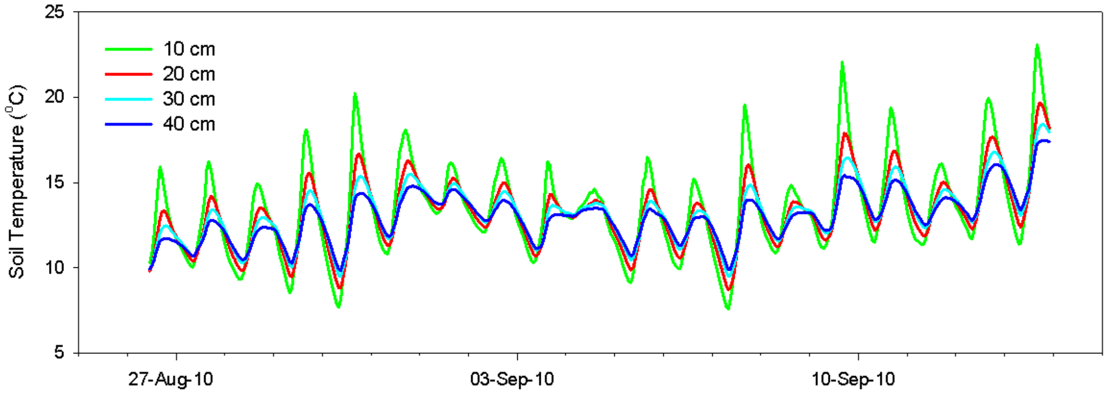


Figure 41 Soil temperature at 4 distances from the pot wall

Soil temperature at 15 cm depth and 4 distances in from the edge of the pot are shown in **Figure 41**. Temperature variation was greatest near the pot wall, and lowest near the centre of the pot. Some records fell below 10°C during the night, but the majority of readings are above this level.

Dareton field site data

Figure 42 illustrates Reference Evapotranspiration (ET_0) measured by the automatic weather station near the trial site, and crop evapotranspiration (ET_C) calculated using appropriate crop coefficients for citrus plantings by 2 methods, FAO 24 (Doorenbos and Pruitt, 1977) and FAO 56 (Allen *et al.*, 1998).

Although it is apparent that the 2 methods of calculating ET_0 give quite different results (blue & green bars), the application of the appropriate K_C to calculate ET_C gives similar results (red & purple bars).

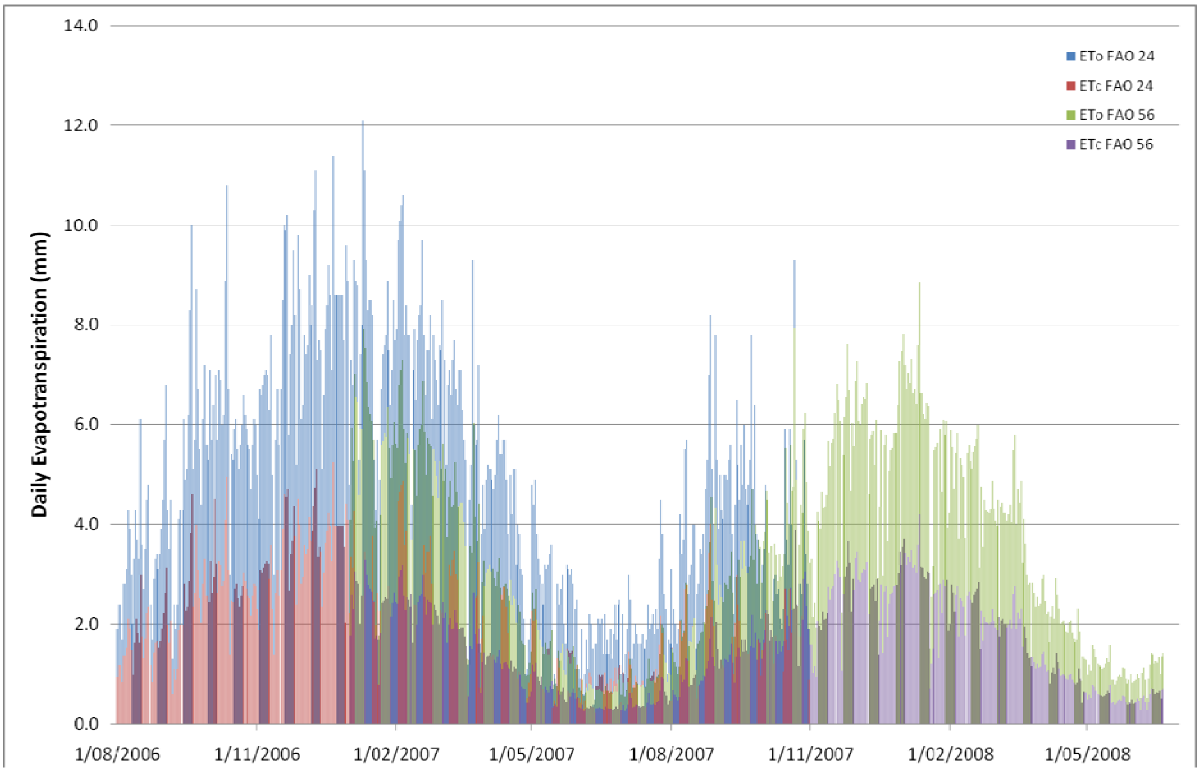


Figure 42 Reference and crop evapotranspiration at Dareton field site

Figure 43 displays EC of soil solutions extracted from four depths using SoluSamplers® at roughly weekly intervals. From the graph it can be seen that EC was below 2.5 dS/m at all times, except for January 8 2007, when the two shallowest samples (25 and 50 cm) registered close to 7.0 and 5.0 dS/m respectively. It is not clear why this occurred.

Beyond these obvious anomalies, the pattern was for soil solutions to have a greater EC during the growing season when water use was highest and fertigation was occurring, and lower during winter when fertigation ceased and water use was minimal.

Figure 44 displays soil solution NO_3^- concentrations. The general pattern is similar to that described above for EC, but without any anomalous readings in January 2007. High NO_3^- readings at 150 cm in January 2007 and January to June 2008 indicate probable leaching of NO_3^- beyond the rootzone.

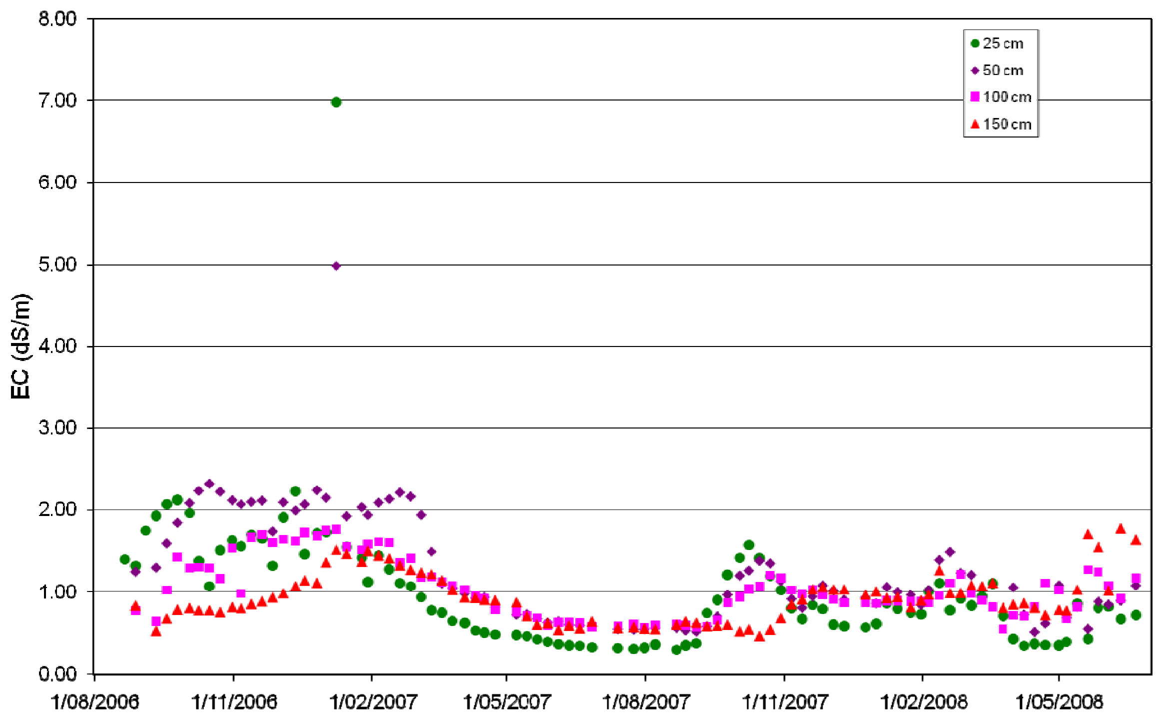


Figure 43 EC of the soil water extracted from 4 depths at the Dareton field site

Modelling Outputs

As noted earlier, modelling to date has been carried out using data from the lysimeters at Loxton only. Further work utilising the field data from the Dareton site is ongoing

Soil water content distribution and water balance

The volumetric moisture contents predicted by HYDRUS 2D/3D model are compared with the measured values obtained from the EnviroSCAN® in **Figure 45**. The model values matched well spatially and temporally with the measured values in all irrigation treatments. However, slight overestimation was observed in values in I_{50} treatment, particularly at 19 days of simulation in the upper 50 cm soil depth. On the other hand, small deviation was also observed in I_{200} treatment where the model underestimated the values of moisture content in surface layers. However, this difference was statistically insignificant, as the root mean square error (RMSE) values ranged between 0.009-0.028, 0.010-0.016 and 0.018-0.036 in I_{50}, I_{100}, I_{200} treatments, respectively.

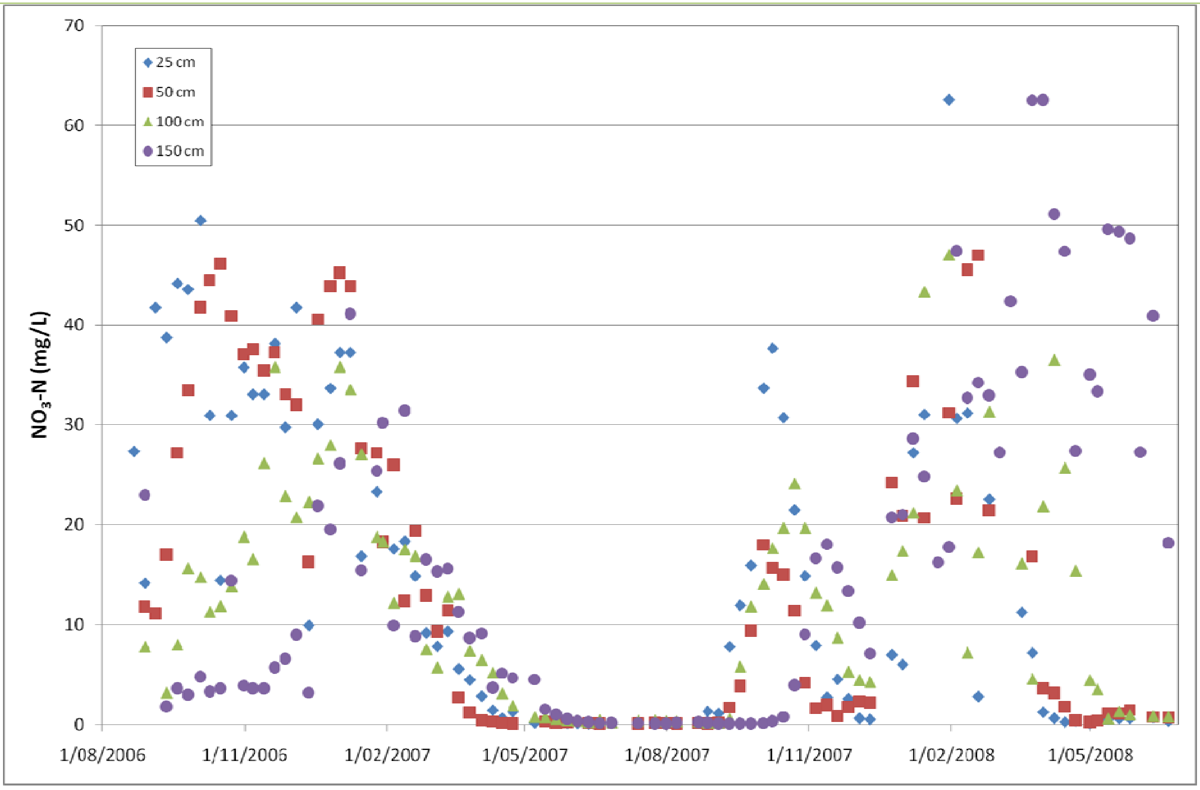


Figure 44 NO_3^--N concentrations in soil water extracted from 4 depths at the Dareton field site

Similarly, the modelled daily and cumulative drainage also showed a close match with the values measured in the lysimeters in all the treatments. Daily drainage volumes for I_{50} treatment are compared in **Figure 46**, and in **Figure 47** the cumulative drainage for I_{200} treatment is shown. It can be seen that the simulated volume of drainage remained slightly under that measured (**Figure 46**), except for the initial higher leaching. However, the total drainage volume matched closely. The high peak at 21 days represents very high rainfall on that day, which also was very well predicted by the model. However, the modelled cumulative drainage volume (**Figure 47**) remained over-predicted until the 23rd day of simulation, after which it overlapped with the measured values till the end of simulation. The close matching of these values indicates that HYDRUS 2D/3D software can successfully be used for the prediction of water movement and drainage flux in the lysimeters.

The modelled values of different water balance parameters for different irrigation treatments are shown in **Table 31**. It can be seen that the absolute volume of root water uptake remained the same in all the treatments, because there was no water stress even in I_{50} treatment, due to the high rainfall received during this period. We also speculate that the assumption of similar root distribution in all treatments has resulted in the same uptake in all treatments. However, the drainage flux increased more than 2 and 4 times respectively in I_{100} and I_{200} treatments as compared to I_{50}, and it matched well with the measured values in the different treatments. Drainage flux varied from 44 to 77% of the total water applied. However, Sluggett, 2010) estimated deep drainage ranged from 6 to 37% in light textured soils growing citrus trees in the Sunraysia region of Australia.

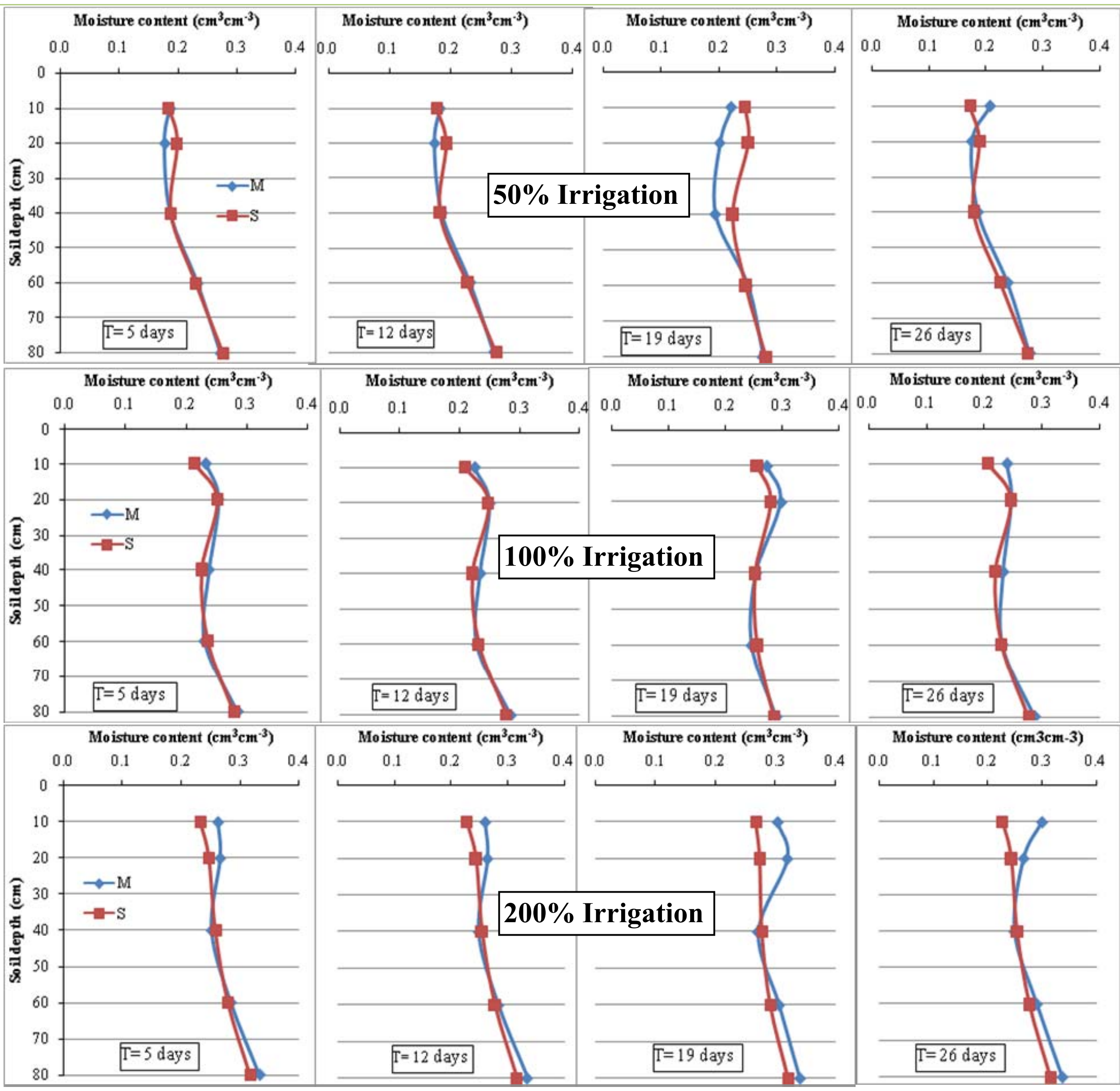


Figure 45 Comparison of measured (M) and simulated (S) moisture content in lysimeter soil

High leaching is bound to occur in highly permeable, coarse textured soil such as the sand/loamy sand used in this study, where water drains easily and quickly from the root zone because gravity dominates (Cote *et al.*, 2003). Preferential flow of water could have also played a part in exacerbating the drainage flux from the lysimeters, though every effort was made to stabilize the soil before the start of measurements. Pakrou and Dillon, 2000) found 78% and 33% higher drainage volumes in repacked lysimeters as compared to monolith lysimeters, in irrigated and non-irrigated paddocks respectively. We suspect that soil disturbance due to excavation, stockpiling and repacking alters the physical fabric of the soil, which can produce unpredictable consequences for water movement. Clearly, there should have been a longer period between when the lysimeters were set up and when they were used.

Figure 46 Temporal changes in observed and simulated periodic drainage volume in 50% water application in lysimeters

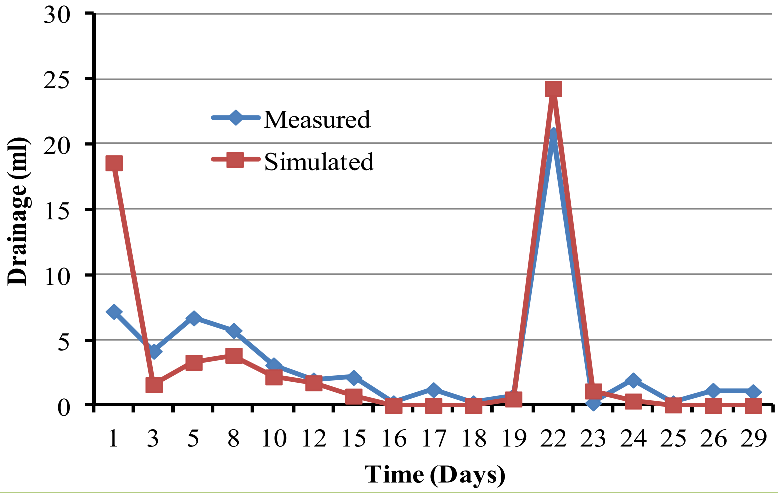
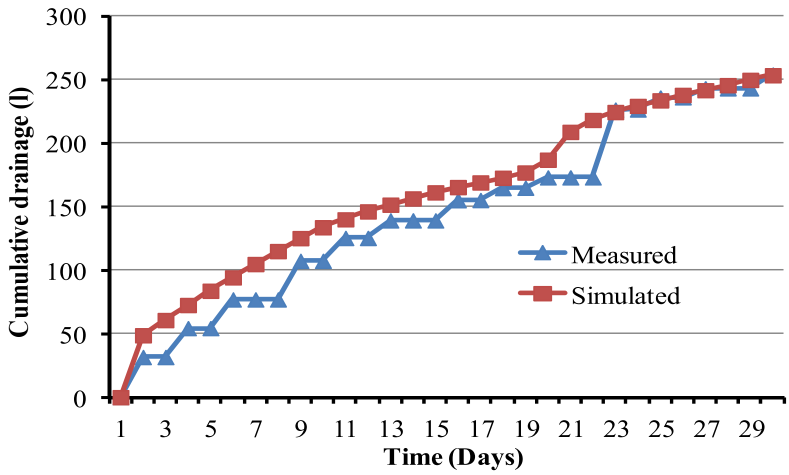


Figure 47 Evolution of observed and simulated cumulative drainage volume in 200% water application in lysimeters



The plant water uptake efficiency values determined for I_{50}, I_{100} and I_{200} treatments were 44, 27 and 18%, respectively. The higher value under lower water application (I_{50}) highlights the better irrigation efficiency in this treatment. Due to the huge drainage flux, the water uptake efficiency drastically reduced in I_{100} and I_{200} treatments.

Nitrate distribution

The modelled NO_3^- distributions at several times after application in different irrigation treatments are shown in **Figure 48**. In I_{50} treatment the NO_3^- concentrated adjacent to the dripper, and slowly moved downward with further application of water and fertigation pulses. On the other hand, in I_{100} and I_{200} the amount of irrigation water increased by 2 and 4 times, and the NO_3^- distributed more or less uniformly throughout the solute plume due to the higher water flux. Consequently, the solute plume also increased in size, resulting in rapid lateral as well as downward movement of NO_3^-. It is worth noting that after 15 days of fertigation all the NO_3^- was leached from the upper 15 cm soil depth just below the dripper in I_{200}, while appreciable amounts of NO_3^- still persisted in the surface layer in the other treatments.

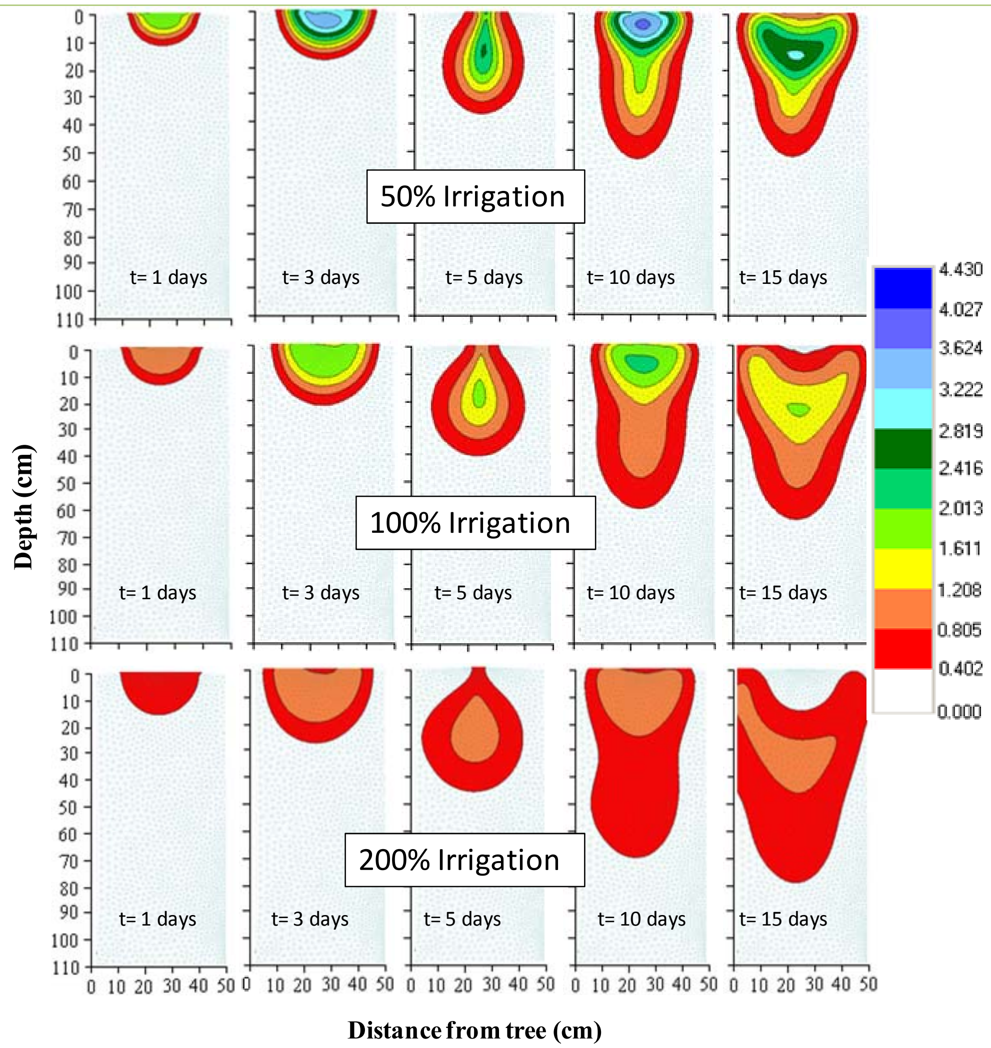


Figure 48 Simulated spatial distribution of NO_3^- (mg cm^{-3}) in soil solution for 50, 100 and 200% irrigation of an orange tree at indicated times after fertigation

Nitrate moved to greater depths (about 80 cm) in I_{200} treatment as compared to I_{50} (55 cm). Hence the amount of water application or rainfall played a key role in the movement of nitrogen in the soil. As a consequence of the high nitrate concentration below the dripper in I_{50}, there was higher nitrate uptake in this treatment as compared to I_{100} and I_{200}, where the dilution effect reduced the concentration in the soil solution.

The simulated NO_3^--N uptake amounted to 29, 25 and 19% of the applied nitrogen, respectively, in I_{50}, I_{100} and I_{200} treatments (**Table 32**). Hence a reduction in NO_3^- uptake of 10% occurred with the increase in water application by a factor of four in the I_{200} treatment. This shows that the irrigation volume plays a key role in regulating the uptake of applied nitrogen by plants, and excess irrigation just after fertigation leads to its rapid movement out of the plant root zone. However, no NO_3^- leaching was simulated in the present study, since the modelling only continued for 15 days after initial application. Most of the applied nitrate was retained in the root zone (71-81%), but was still potentially vulnerable to leaching later in the growing season.

Table 31 Water balance components in different irrigation treatments

Component	Irrigation		
	I_{50}	I_{100}	I_{200}
	mL		
Initial content	217790	251310	252860
Irrigation	56041	112440	224900
Rainfall	57357	57357	57357
Total water input	113398	169797	282257
Uptake by roots	59055	59003	58970
Drainage	58238	143350	253330
Final content	198200	203980	208220
Depletion	19590	47330	44640
	%		
Drainage	44	66	78
Water uptake efficiency	44	27	18

Table 32 Simulated components of fertiliser nitrogen (NO_3^--N) balance under different irrigation treatments

Component	Irrigation		
	I_{50}	I_{100}	I_{200}
	mg		
Added	19986	19961	19961
Taken up by roots	5801	4967	3800
Leached	0.001	0.276	75.88
	%		
Uptake efficiency	29	25	19
Leaching loss	0.0	0.0	0.4

Scenario analysis

The concentration and movement of NO_3^- in soil under different scenarios for I_{50} treatment are shown in **Figure 49**. The movement of NO_3^- seems to be similar in all the scenarios, however, the distribution of NO_3^- in the soil was slightly variable. In scenario PF and PF_3 the concentration of NO_3^- at the end of 2, 7 and 14 days of simulation was higher in the centre of the plume where root activity was maximum. Hence the maximum root NO_3^- uptake of 48% of the applied nitrogen was observed in the PF (fertigation with all pulses of irrigation) scenario followed by PF_3 (47%; fertigation at the end of the irrigation event) as compared to other scenarios (**Table 33**).

Since fertigation was applied in 10 pulses until the 13th day of simulation, the concentration of nitrate remained similar in all scenarios after the fertigation period. Also, the NO_3^- moved to a similar soil depth (60 cm) after 28 days of simulation in all scenarios. The NO_3^- moved out of the upper 15 cm of soil after 21 days and 20 cm after 28 days indicating the potential for leaching of NO_3^- out of the root zone. The fertigation pulse followed by one irrigation pulse for rinsing the irrigation lines (PF_3) or applying fertilizer in low concentration in all pulses (PF) facilitated the movement of nitrogen slightly below the soil surface, in the zone of maximum feeder roots.

Similarly in the I_{100}scenario, the movement of nitrate was more rapid compared to 50% irrigation. The nitrate moved to 80 cm and started leaching out of the domain within 28 days of simulation (**Figure 50**). The resultant distribution of nitrates was longer than in I_{50}, both laterally and vertically. In contrast, the root uptake reduced to approximately 36% of the applied nitrogen in the various scenarios (**Table 33**).

In the I_{200} scenario the nitrate leached out of the domain in appreciable amounts (**Figure 51**). It varied from 18.5 to 21% of the applied nitrogen, being higher in the fertigation with all pulses (PF) treatment (**Table 33**) and less in the PF_3 scenario. At the same time the root uptake in I_{200} reduced to half of the I_{50} treatment, and ranged from 22.0 to 22.7% indicating a drastic reduction in applied fertilizer efficiency and potential for significant loss of applied nitrogen.

We observed that low concentration continuous fertigation with all pulses (PF) had slightly higher root uptake than continuous irrigation along with fertigation (CF) in I_{50} and I_{100}, and the reverse was true in I_{200}. The NO_3^--N leaching was also slightly higher in the former treatment as compared to the latter. This observation further confirms that the pulsing had little impact on water and solute distribution in the soil under optimal irrigation application as compared to continuous irrigation. This observation supports the earlier study made by Phogat *et al.*, 2012.

The 29 days simulation did not produce any NO_3^--N leaching in I_{50} and I_{100}, but considerable leaching occurred in I_{200} treatment. Hence over-irrigation not only led to profuse water loss, but also brought about appreciable leaching losses (approximately 20%) of the applied NO_3^--N in all fertigation scenarios, being less in continuous fertigation. These results imply that fertigation in a short pulse at the end of the irrigation event or low concentration fertigation with all pulses could increase the efficiency of the nitrogen fertigation as compared to other options.

A significant amount of NO_3^--N still remained in the soil; about 53-61% in I_{50} treatment, 64-71% in I_{100} and 58-66% in I_{200} treatment, and preferentially in lower soil layers (**Table 33**). Nitrate at this depth is neither available to the trees, since the majority of active fibrous roots of orange trees are in the top 15-30 cm depth (Alva and Syvertsen, 1991; Zhang *et al.*, 1996), nor can it be easily transformed because of the limited microbial population and available carbon at this depth (Paramasivam *et al.*, 1999; Alva *et al.*, 2006), and this potentially leads to leaching losses to ground water, and ultimately, possibly surface water bodies. Hence, the combination of inadequate management of irrigation and nitrogen fertilizers in commercial agriculture may lead to appreciable NO_3^- losses out of the root zone, and may increase the risk of NO_3^- contamination of ground water aquifers.

Table 33 Components of added nitrogen (NO_3^--N) balance under different irrigation/fertigation scenarios in 50, 100 and 200% irrigation treatments

Scenarios: P, pulse irrigation; C, continuous irrigation; F, fertigation throughout the irrigation event; F_1, fertigation pulse at the beginning of the irrigation event; F_2, fertigation pulse in the middle of the irrigation event; F_3, fertigation pulse at the end of the irrigation event.

		Irrigation management				
		——pulse——				continuous
		Timing of dissolved N fertiliser injection				
		start	middle	end	through-out	through-out
Component	**Measured**	**PF_1**	**PF_2**	**PF_3**	**PF**	**CF**
50% irrigation (I_{50})						
	——mg——					
Added	19986	19986	19986	19986	19975	19960
Taken up	5802	9359	9378	9450	9533	9423
Leached	0.001	0.097	0.091	0.08	0.08	0.11
	——%——					
Uptake efficiency	29.03	46.83	46.92	47.28	47.72	47.21
Leaching	0.00	0.00	0.00	0.00	0.00	0.00
100% irrigation (I_{100})						
	——mg——					
Added	4967	7124	7154	7191	7212	7148
Taken up	19961	19961	19961	19961	19959	19960
Leached	0.28	84	78	72	86	78
	——%——					
Uptake efficiency	24.89	35.69	35.84	36.03	36.13	35.81
Leaching	0.00	0.42	0.39	0.36	0.43	0.39
200% irrigation (I_{200})						
	——mg——					
Added	3780	4410	4465	4534	4458	4472
Taken up	19961	19961	19961	19961	19959	19960
Leached	76	3949	3836	3691	4176	3876
	——%——					
Uptake efficiency	19.03	22.09	22.37	22.72	22.33	22.40
Leaching	0.38	19.78	19.22	18.49	20.92	19.42

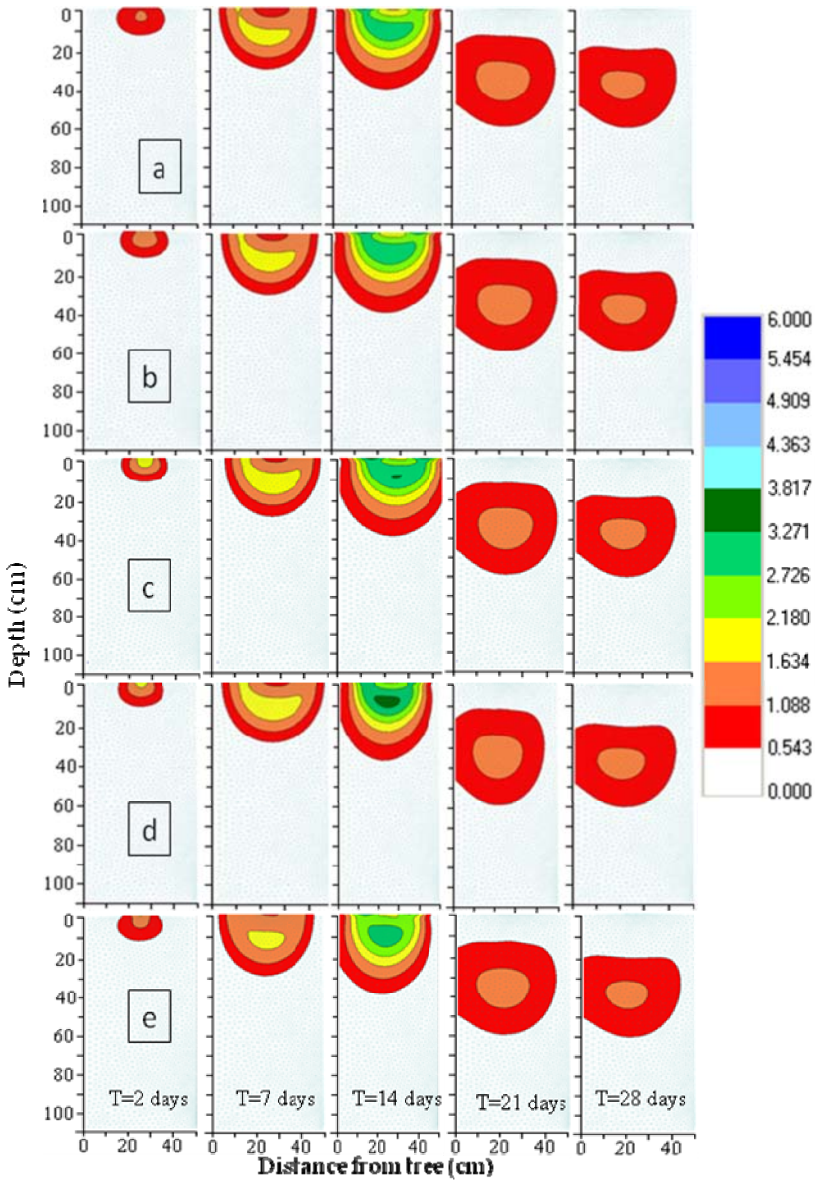


Figure 49 Spatial distribution of NO_3^- (mg cm^{-3}) under 50% irrigation and different pulsed fertigation scenarios

(a) PF1: fertigation at the beginning of a pulsed irrigation event; (b) PF2: fertigation at the middle of pulsed irrigation event; (c) PF3: fertigation at the end of pulsed irrigation event; (d) PF: continuous fertigation during all pulses in a pulsed irrigation event; (e) CF: continuous irrigation and fertigation**.**

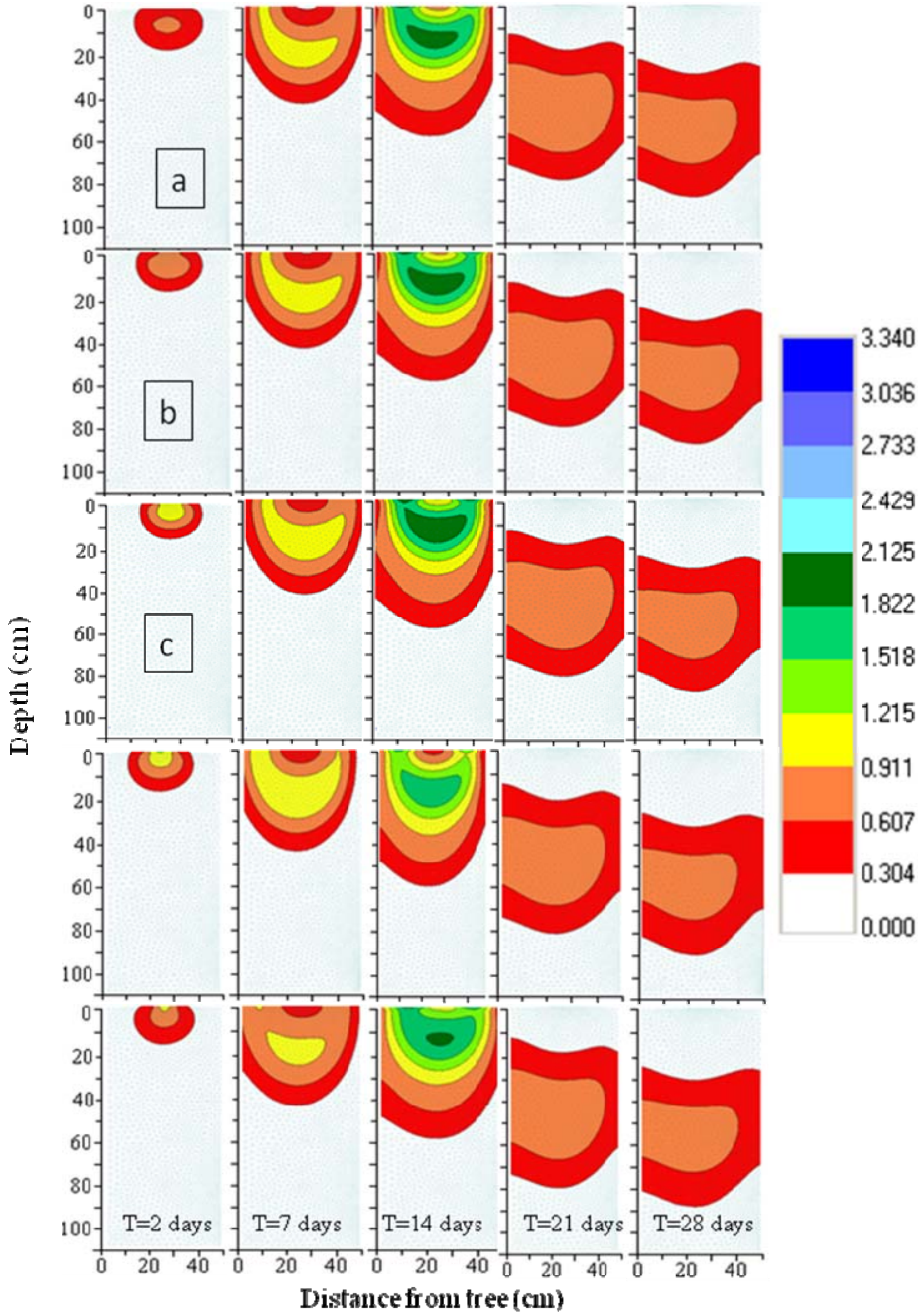


Figure 50 Spatial distribution of NO_3^- (mg cm^{-3}) under 100% irrigation and different pulsed fertigation scenarios

(a) PF_1: fertigation at the beginning of a pulsed irrigation event; (b) PF_2: fertigation at the middle of pulsed irrigation event; (c) PF_3: fertigation at the end of pulsed irrigation event; (d) PF: continuous fertigation during all pulses in a pulsed irrigation event; (e) CF: continuous irrigation and fertigation.

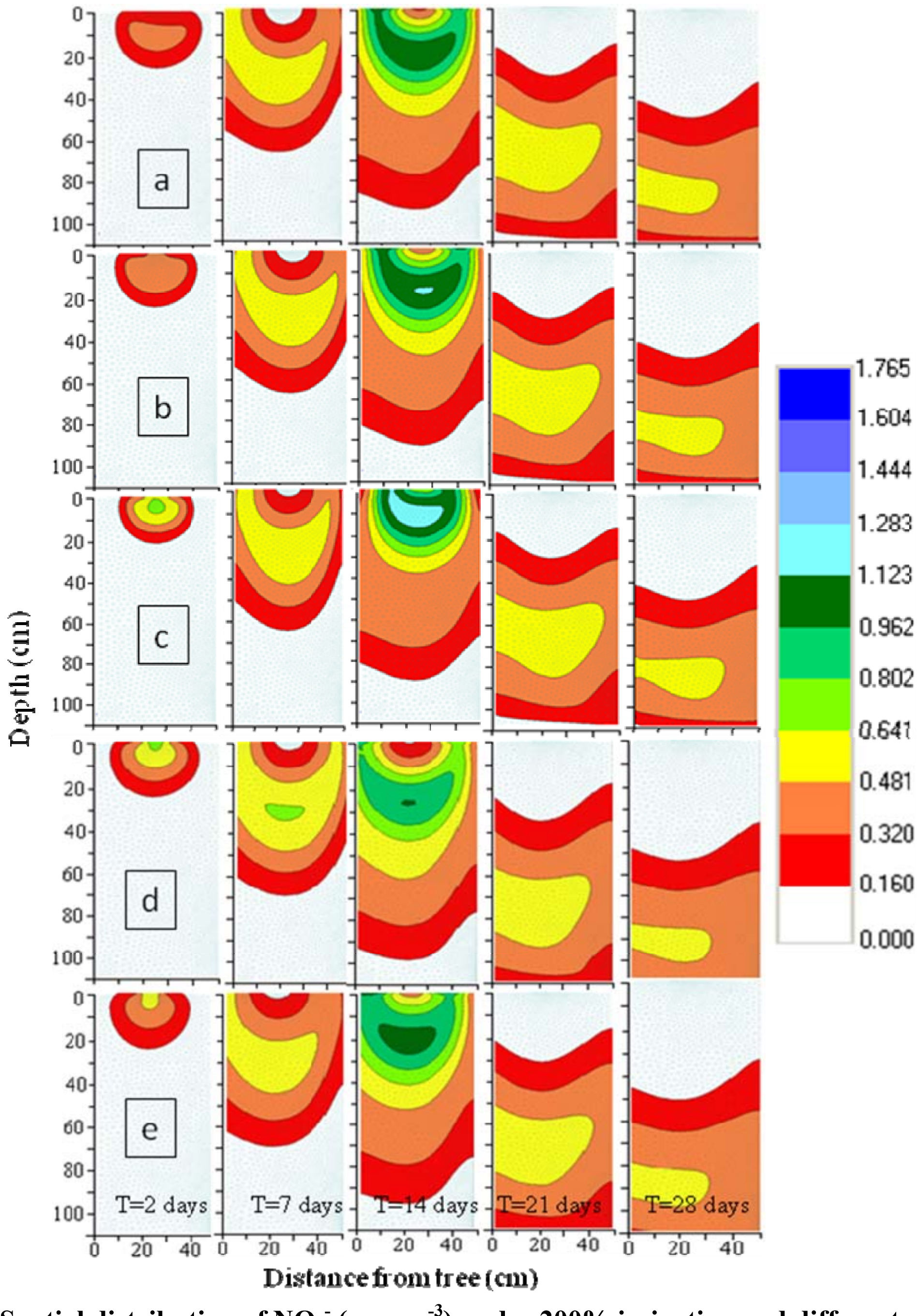


Figure 51 Spatial distribution of NO_3^- (mg cm^{-3}) under 200% irrigation and different pulsed fertigation scenarios

(a) PF_1: fertigation at the beginning of a pulsed irrigation event; (b) PF_2: fertigation at the middle of pulsed irrigation event; (c) PF_3: fertigation at the end of pulsed irrigation event; (d) PF: continuous fertigation during all pulses in a pulsed irrigation event; (e) CF: continuous irrigation and fertigation.

Long term fertigation trial site establishment

Building capacity to enable the assessment of short- and long-term responses to nutrient supply of commercially-relevant citrus scion varieties grafted to commercially-relevant rootstocks, and the impact of fertigation on the soil resource

Summary

This section describes the design and set up of a trial to quantify the long term responses of three selections of navel oranges on five different rootstocks to fertiliser delivered using modern delivery technology. The site being used is a typical wind-blown Mallee land form; free-draining Mallee sand on the top of the dune and a heavier textured soil in the swale. Extensive pre-planting soil sampling suggested a pattern of soil fertility that would normally be expected with such a gradient in soil texture, but also a significant band of acidic soil was present across the site. Thus, the site will allow an assessment of the impact of a key part of modern fertigation systems, namely the adjustment of the irrigation water/dissolved fertiliser solution to a pH of less than 7.

The irrigation/fertigation system was designed to allow the supply of 6 fertiliser mixes, with or without pH adjustment. It is intended that the same relativity will be maintained in the fertiliser regimes imposed over time.

Three navel orange selections (early maturing, mid season maturing and late season maturing) grafted on five different rootstocks were planted in October 2010. Rootstock/scion identity integrity from initial seed/budwood sourcing, through to propagation, grafting and planting was diligently maintained.

The site is large enough to confer credibility with industry, and biometrically robust from a scientific method viewpoint. As such, the site is probably unique in the world, and will be a valuable research and technology transfer resource for the industry for at least 20 years, but industry co-investment will be needed if the site is to reach its potential as a resource for industry.

Introduction

Citrus is a woody evergreen perennial. Mature trees have a large biomass, and considerable “nutrient inertia” as a result. For this reason responses to changes in nutrient supply regimes are unlikely to be immediately noticeable. Modern fertigation systems make altering an orchard’s mineral nutrient supply program a relatively simple matter.

The industry’s fertiliser recommendations are based on trials conducted on trees growing on limited number of rootstocks and using relatively simple fertiliser delivery technology. In practice, those rates are being applied using very sophisticated fertiliser delivery technology to trees growing on a wider range of rootstocks. These systems are based on acidification of the irrigation water/dissolved fertiliser solution, daily irrigations during the growing season, as-frequent applications of dissolved mineral fertilisers in the irrigation water and confining root growth to a much smaller part of the soil volume. These approaches also assume that all rootstocks behave similarly with respect to nutrient uptake. There is no objective evidence that these assumptions are correct, and that these approaches, and the investment in the associated equipment, confers any advantage in terms of productivity. The environmental impact of intensive fertigation is unknown.

To address this knowledge gap a trial site has been set up to quantify the long term response of three selections of navel oranges on five different rootstocks to fertiliser delivered using modern delivery technology. This section describes the site, the variety/rootstock combinations planted, and the experimental design established at the site.

The site

The site chosen for the long term fertigation trial site was originally planted in 1983 to Valencia orange on citrange rootstock. The site was used to demonstrate the benefits and feasibility of drip irrigating citrus. Field days/walks and visits to the site by industry groups were instrumental in the uptake of drip irrigation along the Murray Valley; this increase in uptake of drip irrigation delivered significant water savings. The 2 hectare site was also used to investigate the impact of higher planting densities on tree phenology and productivity. The range of soil textures at the site reflects the range of soil types used for citrus production in south eastern Australia; namely, light sands through to loam and clay loam at depth. The site is essentially the northern half of a typical Mallee sand dune running east-west. Light sands predominate on the top of the dune, and heavier soils predominate in the swale. The soil is a solonized brown soil (Gc1.2) in the calcic xerosol classification (Northcote *et al.*, 1975), and is otherwise known as a Tiltao sand (Northcote, 1951).

The existing trees were skeletonised in December 2008 (**Figure 52**), and the stumps removed in early March 2009. The entire area was ripped to 1.2 m in an east-west direction and then again in a north-south direction with a bulldozer (**Figure 53**).

Figure 52 Valencia orange trees being skeletonised prior to stump removal

Figure 53 Trial site being ripped to 1.2 m following removal of tree stumps

Twenty tonnes of gypsum were then spread across the site, and worked in using a disc plough followed by a light cultivation.

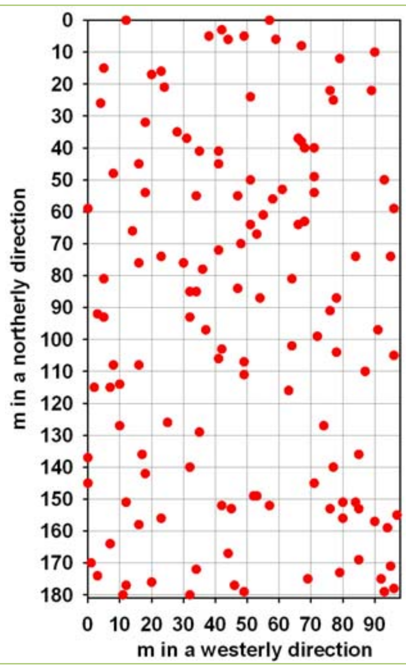
A forage canola (Rangi) was sown at 5 kg per ha^{-1} with 40 kg N as urea, 10 kg P as single strength superphosphate and 40 kg K as potassium sulphate in May 2009, just prior to a strong prediction of 5-10 mm of rain across the region. Although germination was reasonable, subsequent growth was poor due to low winter rainfall in 2009. The crop was killed with 5 L glyphosate ha^{-1} in September of the same year to prevent any seeds that had formed from maturing and developing into a potential weed problem in the future.

Sorghum was sown at 5 kg ha^{-1} directly in to the Rangi residue as a cover crop to prevent wind erosion associated with the strong hot dry northerly winds frequent in late spring and early summer. Urea, equivalent to 40 kg N ha^{-1}, was also sown in with the seed. Although rainfall was well below average over summer there was enough rain to allow the crop to grow sufficiently to warrant slashing twice. This crop was also sprayed out in May 2010, using glyphosate as above, and another cover crop of Rangi sown directly into the trash. This crop competed poorly with volunteer weed species, and all plants growing on the site were sprayed out in September, 2010, with glyphosate. The tree rows were rotary hoed in October that year.

Effectively, the site was rested from citrus for 18 months.

The site's boundaries were pegged out in September, 2010, and 130 soil sampling points across the 1.8 ha site were selected using MS-Excel's random number function. The random distribution of the sampling points (**Figure 54**) was to satisfy the requirements of the kriging algorithm, which interpolates between sampling points to produce a map of trends in a continuous property (*e.g*. pH or cation exchange capacity) of the soil across the site trial, for example cation exchange capacity or pH. The kriging process is more efficacious if there is a wide range of distances between sampling points, as occurs with a random distribution as opposed to a grid sampling pattern.

Figure 54 Distribution of soil sampling points to used to assess soil fertility and chemical variability prior to setting up long term fertigation trial site. Grids are 10 m ×10 m, and points selected at random by MS-Excel's random number function.



A 50 mm diameter soil core was taken at each geo-referenced site with a tractor-mounted hydraulic soil corer, and the 20-50 cm portion of each core was retained.

The samples were air dried and dispatched to a NSW DPI's Wollongbar laboratory for analysis.

The Australian Centre for Precision Agriculture[7] variogram estimation and spatial prediction with error program ("Vesper") was used to produce maps of the key soil properties across the site before planting. A summary of the raw data and data following the kriging process is presented in **Table 34**. Spatial trends across the site in soil pH, CEC, exchangeable K and Ca are presented in **Figure 55**.

[7] www.usyd.edu.au/su/agric/acpa

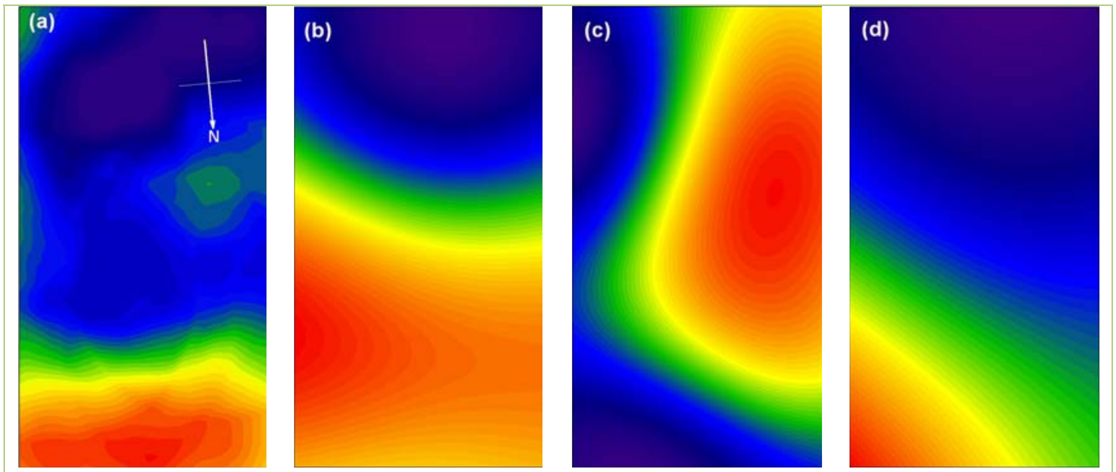


Figure 55 Variograms for soil chemistry and fertility indices for long term fertigation trial site prior to set up.
(a) pH (in $CaCl_2$), (b) NO_3^--N, (c) Colwell P and (d) cation exchange capacity for the 20-30 cm depth interval.
Colour key: lowest [colour bar] highest

Table 34 Ranges and means for raw soil chemistry and fertility indices and ranges for kriged soil chemistry and fertility indices of soil samples collected from the long term fertigation site at Dareton prior to set up

Variate		minimum	mean	maximum
pH	**raw**	3.8	7.1	8.3
	kriged	6.4	-	8.0
			mg NO_3^--N kg^{-1}	
Nitrate	**raw**	1.0	9.8	34
	kriged	6.6	-	13
			mg P kg^{-1}	
Colwell P	**raw**	3.9	25	89
	kriged	23	-	28
			cmol (+) kg^{-1}	
Cation exchange capacity	**raw**	3.4	6.5	12
	kriged	4.8	-	11

Production of grafted trees

Seeds of the rootstocks to be used were germinated in early 2009 as described in the previous section (see Material and methods on page 17). The seedlings were potted up into a sand, peat and bark potting mix in potting bags, hardened off in a glasshouse for 3 months and then moved into a shade house to grow. The rootstock seedlings were suitable for grafting when the stems had reached 8-10 mm in diameter 15-20 cm above the top of the potting bag. Prior to grafting the seedlings were size sorted; only suitably sized seedlings were used. Five rootstocks were used: trifoliate orange[8], Troyer citrange[9], Swingle citrumelo[10], volkerameriana[11] and macrophylla (Wutscher, 1979).

8 http://www.citrusaustralia.com.au/aspdev/resources/documents/Poncirustrifoliatascreenpdf.pdf
9 http://www.citrusaustralia.com.au/gen_pdfs/TroyerCarrizocitrange.pdf
10 http://www.bugsforbugs.com.au/pdf/Swingle%20citrumelo.pdf
11 http://www.bugsforbugs.com.au/pdf/Volkameriana.pdf

Three navel orange selections were used: M7 Early Navel[12], an early maturing selection; Houghton, a mid-season selection of Washington navel[13]; Lane late, a late maturing selection thought to be a sport from a Washington navel tree growing in Curlwaa, south west NSW[14].

Both Houghton and Lane late bud wood were collected from source trees growing on NSW DPI's Dareton site in late October 2009, and grafted (as chip buds) onto the seedling rootstocks within 2 days. Budwood of the early season variety was supplied by Chislett Developments Pty Ltd in February 2010, under an agreement for use of the material for research purposes only.

The 3 budlines were also grafted onto C35[15], a mildly dwarfing citrange rootstock, as buffer trees around the main experimental block.

Depending on weather conditions, the grafted trees were watered 2-4 times per week, fertilised monthly with a complete nutrient soluble fertiliser mix and disbudded as needed.

Experimental design

The variation in the site's soil was greater in a north-south direction compared to an east-west direction. The combination of that variation, the area available and the tree spacing to be used (3 m between trees in a row, and 5 m between tree rows) meant that the rows needed to run east-west, and that there would be 38 rows with 27 trees per row. The first and last trees in each row are on C35 rootstock. The remaining 25 trees consist of 5 groups of 5 trees each, and the trees in each group are on the same rootstock. The first and second trees have the same scion, and the fourth and fifth have another scion. The middle three trees have different scions (*i.e.* early, mid or late navels), and measurements are only to be conducted on the middle 3 trees. The first and fifth tree in each group of 5 trees served as buffer trees. Thus, in each row, there is a tree on C35 at each end of the row serving as border trees, and the trees on which observations and measurements are to be conducted have trees next to them that are on the same rootstock. The groups of trees on the same rootstock were randomised down the row.

There are 6 rows of trees in each block, and the nutritional treatments are assigned randomly to rows within blocks. The nutritional treatments are being applied to whole plots.

The experimental design is a split-split-plot (**Table 35**) and hierarchy of experimental units is set out for a nominal row in **Figure 56**.

Table 35 Components of split-split-plot design for long term fertigation trial.

Block	Block (1-6)
Whole plot	Tree rows within blocks (1-6)
Sub-plot	Middle 3 trees in each group of 5 trees on the same rootstock (1-5)
Sub-sub-plot	Individual tree (1-3)

The major experimental variables are nitrogen supply (50, 100 and 200% of the concentration of N in nutrient solution associated with maximum growth/N uptake, as determined in the sand culture experiments) and ±pH trimming with the capacity for P and K supply to be varied in a similar manner as N supply. Nutritional treatments are to be applied to whole rows .

[12] http://www.chislettnavel.com.au/M7.html
[13] http://www.citrusaustralia.com.au/aspdev/resources/documents/Washington7-02.pdf
[14] http://www.citrusaustralia.com.au/aspdev/resources/documents/LaneLate7-02.pdf
[15] http://www.citrusaustralia.com.au/PDFs/resources/varieties/C-35_citrange_sml.pdf

Tree nr.	Split-split-plot design hierarchy	Rootstock	Scion seasonality
1	(buffer)	C35	mid
2	(buffer)	vol	mid
3	sub-sub-plot	vol	mid
4	sub-sub-plot	vol	late
5	sub-sub-plot	vol	early
6	(buffer)	vol	early
7	(buffer)	mac	early
8	sub-sub-plot	mac	early
9	sub-sub-plot	mac	late
10	sub-sub-plot	mac	mid
11	(buffer)	mac	mid
12	(buffer)	Troy	mid
13	sub-sub-plot	Troy	mid
14	sub-sub-plot	Troy	late
15	sub-sub-plot	Troy	early
16	(buffer)	Troy	early
17	(buffer)	tri	early
18	sub-sub-plot	tri	early
19	sub-sub-plot	tri	late
20	sub-sub-plot	tri	mid
21	(buffer)	tri	mid
22	(buffer)	Swi	mid
23	sub-sub-plot	Swi	mid
24	sub-sub-plot	Swi	early
25	sub-sub-plot	Swi	late
26	(buffer)	Swi	late
27	(buffer)	C35	late

Figure 56 Split-split-plot hierarchy for a single nominal row in the long term fertigation trial site

Irrigation system infrastructure

A schematic representation of the head works installed to supply N, P and K at variable rates to specific rows of trees is presented in **Figure 57**.

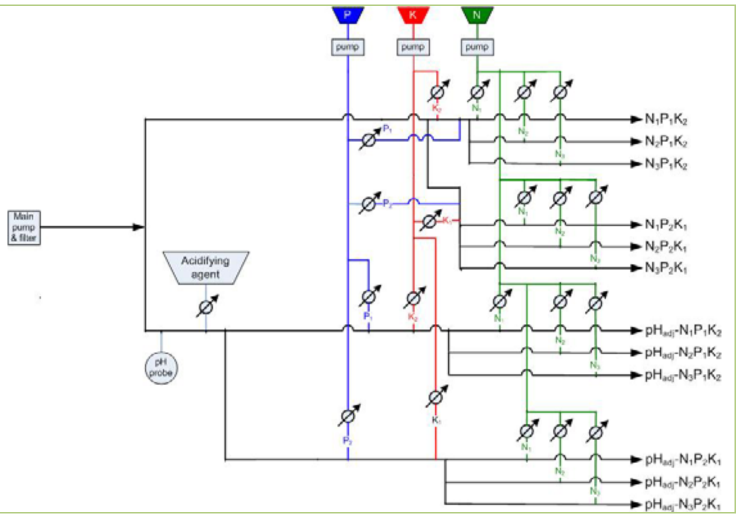


Figure 57 Schematic representation of irrigation/fertigation head works Subscripts refer to concentrations to be supplied; 1, 50% of maximal rate; 2, 100% of maximal rate; 3, 200% of maximal rate

The site's future

The site is large enough to confer credibility with industry, and sufficiently biometrically robust to be scientifically credible. The site is "purpose built", and, as such is probably unique in the world. The site will be a valuable research and technology transfer resource for R&D providers and industry for at least 20 years.

In addition, the differing seasonalities of the three scion selections mean that it may be possible to use the trees to investigate the physiology of biennial bearing at some point in the future.

Further support, particularly from industry, for data collection during the medium to longer term phase of the trees' productive life will be needed. At the time of writing, a number of applications had been made without success to Horticulture Australia Limited and federal and state government funding agencies and schemes to secure support for maintenance and base line data collection. The citrus industry's current levy arrangements, an emphasis on marketing in its R&D investment portfolio and the poor returns to citrus producers related crop size management issues, have made, and will to continue to make, gaining short and long term support for the site difficult. NSW DPI will continue to maintain the site, but is unable to undertake any detailed scientific activity without co-investment.

Workshops, fact sheets and other extension outputs

Disseminating knowledge to manage modern fertigation systems

Workshops

Citrus nutrition

A citrus nutrition workshop was developed and delivered as four half day sessions. The workshop incorporated outdoor activities to break up the presentation of the more formal material, to discuss the practical aspects of citrus nutrition. The practical aspects include how to estimate crop load (**Figure 58**), visually assess the nutritional status of a tree and the correct methodology to sample leaves for mineral nutrient analysis (**Figure 59**). Participants were given "homework" between sessions; growers were asked to assess crop loads on their properties and to prepare a nutrition plan using the nutrient management planner spreadsheet and fertiliser planner tool (**Figure 60**) (described in next section).

Four workshops were conducted during the course of the project, and a total of 50 citrus growers attended. The workshops will continue be to be conducted throughout the citrus growing regions of Australia pending demand.

Figure 58 Citrus nutrition workshop participants using a counting frame to estimate crop load

Figure 59 Citrus nutrition workshop participants showing leaves to sample for mineral nutrient analysis

Figure 60 Citrus nutrition workshop participants preparing nutrition plans and comparing costs fertilisers and suppliers

Soil solutions

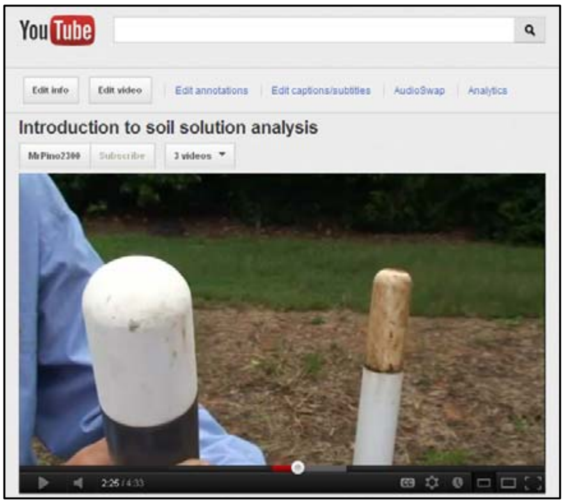
Although soil solution extraction has been a research tool for about 100 years, its use as a monitoring tool in commercial orchards has only been a recent development. Workshops, a factsheet and video were developed to promote the technology.

Two workshops were developed; one targeting irrigators and the other ("Solutes Master Class") targeting agricultural research and extension personnel. The latter was facilitated by the CRC for Irrigation Futures, assumed a basic level knowledge of soil chemistry and plant physiology and focused more on the technical aspects of soil solution monitoring. The master class drew upon the knowledge of Dr Richard Stirzaker, Steven Falivene and Dr Tapas Biswas. Three master classes were conducted during the project with a total of 36 participants.

The information developed at the master class was used as the basis of a workshop for citrus producers, which focused more on the basics of soil science and the practical use and interpretation of soil solution monitoring. Two workshops were held in the Riverina and Sunraysia, and 12 citrus producers participated. Feedback from participants suggested better knowledge of soil science was needed to better utilise soil solution monitoring information. A soil science workshop is being developed to address this need, and the soil solution workshops were put on hold to facilitate this. Potentially, participation in the soil science workshop may be a prerequisite to participating in the soil solution workshop.

A fact sheet introducing soil solution monitoring was prepared (see details below), and a video is being developed to be featured on NSW DPI's YouTube site (**Figure 61**).

Figure 61 Screen shot of video on soil solution analysis being prepared for YouTube



Factsheets

Four factsheets were prepared during the course of the project.

- *Fertigation: delivering fertiliser in the irrigation water*. Primefact 1089[16]. NSW DPI, Orange (**Figure 62**)
- *Soil solution analysis*. Primefact 1143[17]. NSW DPI, Orange

[16] http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/378564/Fertigation-delivering-fertiliser.pdf
[17] http://www.dpi.nsw.gov.au/agriculture/horticulture/citrus/management/nutrition/soil-solution-analysis

- *Fertigation equipment for use in orchards*. Primefact 1144[18]. NSW DPI, Orange
- *Guidelines for Fertigating Citrus Orchards*. Sustainable Irrigation Management Update. National Program for Sustainable Irrigation[19]

Videos

Videos are still in production, but draft versions are listed:

- Soil solution analysis preparation www.youtube.com/watch?v=zda3-NKdLSk
- Leaf analysis – preparation www.youtube.com/watch?v=H6UQNlas4Vg
- Leaf analysis – leaf selection www.youtube.com/watch?v=IF1DuZ6TO41
- Leaf analysis – leaf washing www.youtube.com/watch?v=ak7tPphyGKA
- Leaf analysis – interpretation www.youtube.com/watch?v=dC8V3_DOJ-1

Other videos planned for production in the future include:

- Solution sampler and tensiometer installation
- How to make a soil solution tube
- How to use the fertiliser planner tool
- How to use E-schedule

Conference presentations

- Falivene, S. *Soil Solution Monitoring in Australi*a. Oral presentation at 2008 CRC for Irrigation Futures Annual Research Forum, Canberra.
- Falivene, S. *Soil Solution Monitoring in Australia*. Oral presentation at 2009 Irrigation Australia Conference, Swan Hill.
- Falivene, S. *Integrated Advanced Fertigation of Young citrus: First year experience & drip irrigation management tools*. Poster presentation at 2009 Irrigation Australia Conference, Swan Hill.
- Falivene, S. *Integrated advanced fertigation of citrus (IAF): first two years experience of soil solution monitoring*. Poster presentation at 2010 Irrigation Australia Conference, Sydney.
- Falivene, S. E-*Schedule: affordable new software to improve irrigation scheduling*. Poster presentation at 2010 Irrigation Australia Conference, Tanunda.
- Phogat, V., Skewes, M. Cox, J.W., Alam, J. and Grigson, G. *Minimising drainage and nitrate losses under navel orange*. Poster presentation at 2011 Citrus Australia Conference, Nuriootpa

Published outputs

Phogat, V.; Skewes, M.A.; Cox, J.W.; Alam, J. and Grigson, G. 2012. Simulation of water and nitrate dynamics in a lysimeter planted with an orange tree. *Agricultural Water Management* (submitted)

[18] http://www.dpi.nsw.gov.au/agriculture/horticulture/citrus/management/nutrition/fertigation-equipment
[19] http/www/npsi.gov.au

WWW.INDUSTRY.NSW.GOV.AU

primefacts

FOR PROFITABLE, ADAPTIVE AND SUSTAINABLE PRIMARY INDUSTRIES

FEBRUARY 2011 | PRIMEFACT 1089

Fertigation: delivering fertiliser in the irrigation water

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Introduction

The delivery of dissolved mineral fertilisers to the roots of crops in the field using irrigation water is known as 'fertigation'. The use of fertigation is gaining popularity because of it's efficiencies in nutrient management, time and labour and potentially a greater control over crop performance.

The supply of dissolved mineral nutrients to plant roots has been a research tool for at least 100 years. The mixture of water and dissolved nutrients is known as the 'nutrient solution', and the concept of growing land plants without soil has become known as 'hydroponics' (from the Greek words for water and labour, namely *hydro* and *ponos*, respectively)[1].

The concept had its first practical application in the 1940s when vegetables were grown in a soilless solution culture. This is still widely practiced in the production of high value annual vegetable crops under protective structures, and is sometimes referred to as nutrient film technique, or NFT. In 'soilless solution' culture, all the plant's mineral nutrient requirements must be supplied in the irrigation water.

[1] http://en.wikipedia.org/wiki/Hydroponics

Fertigation represents a natural extension of the hydroponics concept, and is now widely practiced in horticultural industries, particularly permanent plantings of crops such as citrus, olives and almonds. Fertigation is most successful when combined with drip irrigation.

Advantages

The advantages of supplying mineral nutrients to crop roots using fertigation include:

- Reduced delivery costs (no need to broadcast fertilisers, leading to less soil compaction in the inter-row areas, less fuel usage and lower labour requirements).
- Greater control over where and when nutrients are delivered, leading to greater fertiliser use efficiency.
- More control over crop behaviour through targeted application of specific nutrients during particular stages of crop development.
- Potential for reduced fertiliser losses (due to immobilisation within or leaching below the rootzone) by supplying small amounts often.

Disadvantages

These include:

- Greater capital costs associated with the equipment needed to dissolve and inject the fertiliser into the irrigation water.
- Higher operating costs associated with using technical grade fertilisers as opposed to agricultural grade fertilisers.
- Chemical reactions between some types of fertilisers when mixed, potentially causing significant equipment blockages.

NSW Industry & Investment

Equipment

The level of sophistication, and associated capital cost of fertigation equipment varies greatly. This aspect will be covered in more detail in another Primefact, but some general comments about mixing tanks and control units are included in this document.

Mixing tanks: Many fertigation systems are designed with three mixing tanks to allow the supply of up to three different fertiliser mixes in a single irrigation, but at different times during that irrigation. Sometimes only a single tank is used, with different fertilisers being supplied in different irrigation shifts (Figure 1).

Using multiple tanks reduces the time required to manage a system, and makes it easier to supply small doses of different fertilisers during every irrigation event without having to frequently replenish each tank. However consideration must be given to allowing sufficient time for one fertiliser to be flushed through the system before another fertiliser is introduced (Figures 2 & 3).

Control systems: Various control units are available that allow irrigation pumps to be turned on at pre-set times, for irrigation sections to be turned on and off according to a pre-determined program, and also systems that control when and how much of each fertiliser mix is to be injected into the irrigation water.

Equipment is also available to monitor and modify the electrical conductivity (EC) and pH of the water/nutrient mix (Figure 4). EC is often used as an indirect measure of the amount of fertiliser being injected into the irrigation water; higher EC readings are indicative of high amounts of fertiliser being injected.

Figure 1. Single fertigation tank in a citrus orchard. This type of equipment is commonly installed down stream of a valve that services a distinct management unit (i.e. block). It generally can only supply a single fertiliser at a time and requires manual operation.

Figure 3. PVC pipes taking separate dissolved fertilisers to the injection point.

Figure 2. Multiple mixing tanks allow the supply of different fertilisers in the one irrigation shift.

Figure 4. Front panel of a fertigation system control unit that allows setting of water/nutrient mix, electrical conductivity (EC) and pH.

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Fertilisers Applied

All mineral nutrients can be supplied to plant roots using fertigation. Generally though, it is usually only the major nutrients — nitrogen (N), phosphorus (P) and potassium (K) — that are supplied using this method. However calcium (Ca) and magnesium (Mg) are sometimes supplied. Sulphur (S) is often inadvertently supplied when fertilisers such as potassium sulphate and magnesium sulphate, are used to supply K and Mg, respectively.

Using fertigation to supply the other essential micronutrients such as boron (B), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) and molybdenum (Mo) is possible, but these nutrients are generally applied as foliar sprays because only small amounts are needed.

Forms of Fertilisers

Agricultural grade fertilisers are generally not suitable for use in fertigation systems because of the amount of impurities present, which may be insoluble and lead to dripper blockages. For this reason technical grade fertilisers are normally required in fertigation systems because they have fewer impurities and proportionally higher levels of the desired mineral nutrients.

Single, double and triple-strength superphosphate and rock phosphate are unsuitable for use in fertigation systems.

Fertilisers suitable for use in fertigation systems come as technical grade salts (e.g. potassium sulphate), acids (e.g. nitric acid), bases (e.g. potassium hydroxide), polymers (e.g. polyphosphate) or chelates (e.g. iron EDTA). They are almost exclusively injected into the irrigation water already in solution (i.e. pre-dissolved in water).

Insoluble sources of calcium (Ca) are an exception to this rule. For example, gypsum, which is sometimes used to help remove excessive amounts of sodium ions (Na^+) from the soil profile and improve soil structure, can also be introduced into the irrigation water. However it must be very finely ground and the source tank, constantly agitated to prevent settling of the fine particles and to prevent dripper blockages.

The amount of each fertiliser that can be completely dissolved in a given volume of water is different, and highly dependent on the temperature of the water. Less of a given fertiliser can be dissolved in cold water (i.e. <5°C) than can be dissolved in warm water (i.e. >15°C). There are guides and charts available on the amount of various fertilisers that can be dissolved in a given volume of water as a function of the temperature of that water.

Another potential problem with fertigation systems is with the mixing of fertilisers. There is the potential for negatively charged ions (anions) from one fertiliser to react with positively charged ions (cations) from another fertiliser to form an insoluble precipitate (clump). This can lead to clogging problems in the irrigation system. The major danger lies with calcium (Ca^{2+}) which forms insoluble precipitates with phosphate (PO_4^{3-}) or sulphate (SO_4^{2-}). Compatibility and mixing charts for different fertilisers are available.

Open hydroponics

Fertigation approaches vary from simply using the irrigation water to supply the basic nutrients (i.e. N, P and K) in a few applications per year while still relying on the soil to supply all other nutrients, through to those that supply the crop's complete nutrient needs in small doses sometimes on a daily basis.

In the latter approach (daily irrigations) the soil essentially only provides the mechanical support for the crops' roots and acts as a storage bank for the water and nutrients added. This approach has become known as 'open hydroponics'. Another feature of this approach may include adjusting the pH of the irrigation water/nutrient mix; a practice know as 'pH trimming'.

Some open hydroponic systems have fewer drippers per plant, and water is applied more frequently in very short irrigations (pulsing). This results in a much smaller proportion of the available rootzone being wetted, confining root growth to the wet soil. For example, under open hydroponics, citrus roots can be confined to a root volume as small as 0.5 m^3 compared to 6–10 m^3 under conventional irrigation/fertigation. (Figure 5).

drip line
feeder roots
wetted strip produced along the lateral

Figure 5. Cross-section along a plant row showing a typical wetting strip pattern under drippers.

The reduced root volume also means that the amount of water held in that soil volume is much less, and so the interval between field capacity and wilting point, i.e. the time interval between irrigation events, is much shorter compared to conventional irrigation. With open hydroponics soil moisture monitoring and the ability to supply water on demand are critical to prevent trees suffering water stress.

The major potential benefit of the open hydroponics approach is – better control over the delivery of water and nutrients to the plant roots due to the restricted volume of wetted soil. However, it is also potentially the weakest link because a very high level of management skill and greater capital investment are required when using open hydroponics compared to simpler approaches. Anything less than best management can very quickly lead to major problems, ranging from reduced yield and quality through to crop death. Cutting corners on equipment may mean that some potential efficiencies are not made.

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Using fertigation to manage crop performance needs to be based on a good knowledge of when and to what extent each mineral nutrient is taken up by the crop's roots and how it affects crop growth, development, and yield. With some open hydroponics systems, which essentially ignore soil fertility, this knowledge is even more critical. There is a tendency to assume that all crops behave similarly, but this is not the case. It must be stated that there are still major knowledge gaps in this area for specific crops. Another gap in technology is the ability to measure crop nutrient status in 'real time', and to interpret that information correctly and use it to manage the fertigation system.

Summary

Fertigation potentially offers many advantages over conventional approaches to managing a crop's fertiliser needs.

While fertigation is an exciting and potentially profitable addition to horticultural production systems, it also requires significant investment in equipment, advanced management skills, constant monitoring and an understanding of the specific crop's nutrient needs.

Suggested reading

- Falivene, S 2008, *Soil Solution Monitoring in Australia*, Co-operative Research Centre for Irrigation Futures.
- Giddings, J 2005, *Drip Irrigation – A Citrus Grower's Guide*, NSW Department of Primary Industries, Orange.
- Hoagland, DR & Arnon, DI 1938, 'The water culture method of growing plants without soil', *Circular of the Californian Agricultural Experiment Station*, 347: p. 39.

Images courtesy of Industry & Investment NSW.

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Figure 62 Factsheet on general principles of fertigation

Fertiliser planning tool and E-Schedule

Tools to make better irrigation and fertiliser decisions

Summary

Making irrigation scheduling and fertiliser application decisions can be difficult and confusing, and while there is a huge amount of information available to assist in these decisions, the integration of all of this information to make a simple decision can be a daunting task.

Two MS-Excel spreadsheet-based decision support tools were developed to assist irrigators to make well-informed decisions regarding fertiliser and irrigation applications. The spreadsheets bring together the many pieces of information available under a single umbrella, assisting in the interpretation of that information, and helping the user make informed judgements.

The fertiliser planning tool makes planning fertiliser programs more efficient and cost effective by:

- simplifying the comparison of various fertilisers and sources;
- enabling development of a fertiliser program more suited to crop load; and
- simplifying the planning of fertiliser supply logistics for individual management units and whole farms.

E-Schedule, an irrigation scheduling decision support tool, makes it simpler to bring together all the disparate pieces of information needed to make an informed irrigation scheduling decision. The package does this by:

- automatically downloading historical data and weather predictions from the internet;
- providing ET_o estimates based on the 4 most commonly used ET_o equations;
- using predictive weather data to project ET_o into the near future;
- allowing customisation of weather data to suit site conditions.

E-Schedule's development and adoption may be hampered by threats to on-going access to all the weather prediction components in a stable format.

Fertiliser planner tool

An Excel-based spreadsheet fertiliser planner was developed out of the necessity to make planning fertiliser programs more efficient and simpler, and to assist citrus producers to compare sources and costs of various fertilisers. The planner contains multiple sheets that allow users to plan different programs for up to 12 management units within a property.

The main sheet is the nutrition planner (**Figure 63**). Details of the planned fertiliser program are entered and the spreadsheet calculates the rates of each element (*i.e.* N, P, K, Ca *etc.*) in kilograms per hectare, and the cost. This sheet allows fine tuning of programs and fertilisers to meet the desired application rates for the lowest cost. Users can enter an estimate of crop size and the spreadsheet will calculate likely nutrient removals, which can form the basis of planning amounts to be supplied.

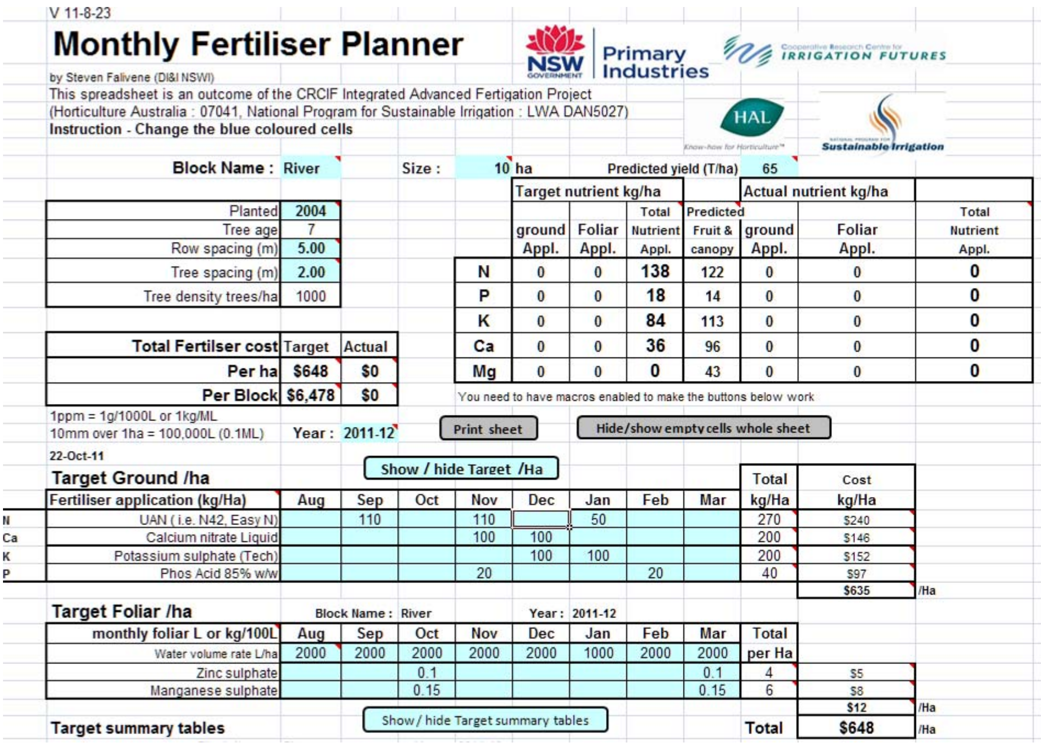


Figure 63 Nutrition planner sheet setting out timing and amounts

Growers enter fertilisers to be used, the rates and the timing of application. Costs are automatically calculated using the latest costs entered into the fertiliser costs analysis sheet.

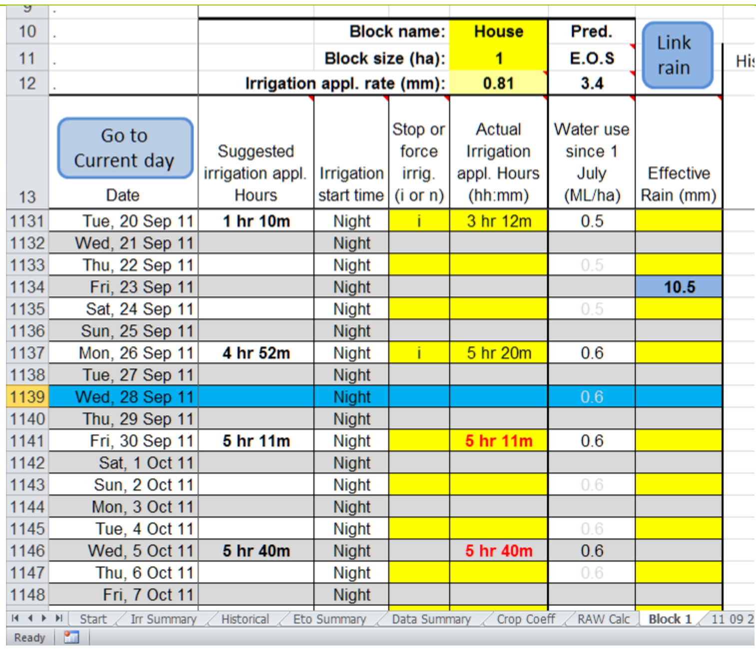
The fertiliser planner tool has been successfully used as both a teaching aid in the citrus nutrition workshop and by workshop attendees in their daily management. A leading citrus packer/consultant has used the planner to prepare fertiliser plans for all of their citrus fruit suppliers.

E-Schedule

E- Schedule is an Excel spreadsheet-based irrigation management and scheduling decision support tool that evolved from the recognition of the difficulty many irrigators experience trying to integrate all the disparate pieces of information together and arrive at an estimate of irrigation needs for an irrigation management unit. The potential for the package to deliver benefits to irrigators more widely was recognised and consequently more extensive resources were invested to develop the concept further.

The package has multiple worksheets to house various calculations and records. The main (“Block”) worksheet contains the core information advising irrigators when and how much to irrigate (Figure 64). Up to 12 block sheets can be set up in a single copy of E-Schedule, representing 12 irrigation management units.

The block sheet integrates historical weather data, weather predictions, crop coefficients (K_c) and estimates of readily available water (RAW) from the other sheets to calculate cumulative crop water use and likely water use over the coming few days. All that information is then used to determine when and how long the next irrigation needs to be.



10		Block name:			House	Pred.	Link rain
11		Block size (ha):			1	E.O.S	
12		Irrigation appl. rate (mm):			0.81	3.4	
13	Go to Current day Date	Suggested irrigation appl. Hours	Irrigation start time	Stop or force irrig. (i or n)	Actual Irrigation appl. Hours (hh:mm)	Water use since 1 July (ML/ha)	Effective Rain (mm)
1131	Tue, 20 Sep 11	1 hr 10m	Night	i	3 hr 12m	0.5	
1132	Wed, 21 Sep 11		Night				
1133	Thu, 22 Sep 11		Night			0.5	
1134	Fri, 23 Sep 11		Night				10.5
1135	Sat, 24 Sep 11		Night			0.5	
1136	Sun, 25 Sep 11		Night				
1137	Mon, 26 Sep 11	4 hr 52m	Night	i	5 hr 20m	0.6	
1138	Tue, 27 Sep 11		Night				
1139	Wed, 28 Sep 11		Night			0.6	
1140	Thu, 29 Sep 11		Night				
1141	Fri, 30 Sep 11	5 hr 11m	Night		5 hr 11m	0.6	
1142	Sat, 1 Oct 11		Night				
1143	Sun, 2 Oct 11		Night			0.6	
1144	Mon, 3 Oct 11		Night				
1145	Tue, 4 Oct 11		Night			0.6	
1146	Wed, 5 Oct 11	5 hr 40m	Night		5 hr 40m	0.6	
1147	Thu, 6 Oct 11		Night			0.6	
1148	Fri, 7 Oct 11		Night				

Figure 64 Block sheet of the E-Schedule irrigation scheduling decision support tool

The current day (blue row) and predictions of future irrigation events based on the current settings (red text).

The Elders' weather web site[20] is the current source of weather predictions sourced by E-Schedule, but occasional minor layout changes cause E-Schedule's download function to fail. Functionality can be restored after a minor manipulation of the computer code to recognise the new layout, but the long-term viability of using this source of weather predictions is likely to be problematic. E-Schedule will be upgraded to utilise the Bureau of Meteorology's (BoM) improved predictive weather service to be available in July 2012. This will improve E-Schedule's accuracy and stability.

In theory, the most appropriate data to base a calculation of ET_o are weather data collected as near as possible to the site being irrigated. Data collected on site include weather conditions over the last few hours, as opposed to BoM data; for example, minimum and maximum temperatures for the previous day. However, on-site weather stations need to be appropriately sited, and sensors regularly calibrated and maintained. One solution may be to use on-site weather stations as a back-up if BoM data are unavailable. Local/on-site weather stations can also provide data useful in calibrating BoM wind data.

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