NATIONAL PROGRAM FOR
Sustainable Irrigation

Open Hydroponics: Risks and Opportunities

Stage 1

Water, Nutrient and Salt Balance Simulations

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Abbreviations

$[N]_t$	Concentration of nitrogen in the root-zone at time t
$[N]_{t-1}$	Concentration of nitrogen in the root-zone at time t-1
CR	Upward flux of water into the root-zone by capillary rise
D	Below root-zone drainage
EC_e	Soil salinity
ET_c	Crop evapotranspiration
ET_o	Reference crop evapotranspiration
f	Fraction of direct beam solar radiation intercepted by the tree’s foliage
f_{WZ}	Wetted fraction of available soil defined on the horizontal plane by the row and tree spacing
I	Applied irrigation
$N_{applied}$	Amount of nitrogen applied
$N_{drainage}$	Amount of nitrogen leaked below the root-zone
$N_{efficiency}$	Plant uptake efficiency of nitrogen
OH	Open hydroponics
R	Rainfall
RAW	Readily available water
R_{off}	Surface run off
RZD	Root-zone depth
$S_{applied}$	Amount of salt applied
$S_{drainage}$	Amount of salt leaked below the root-zone
SF_{in}	Horizontal sub-surface flow into the root-zone
SF_{out}	Horizontal sub-surface flow out of the root-zone
SWC_t	Soil water content at time t
SWC_{t-1}	Soil water content at time t-1
SWC_{UL}	Upper limit soil water content
$WZSWC_t$	Average soil water content in the wetted zone at time t
$WZSWC_{UL}$	Upper limit soil water content in the wetted zone

Introduction

The aim of open hydroponics (OH) is to apply nutrients and water to an orchard to match the crop's requirement for optimum vegetative growth, yield and fruit quality. Nutrients are injected continuously into a drip irrigation system and irrigation is applied to maintain soil water content close to field capacity. Nutrients and water are not recycled in an OH system.

The number of emitters per plant in an OH system is less than a conventional drip irrigation system to enable the non-stop or high frequency daytime application of water and nutrients. Fewer emitters per plant means that the wetted soil volume will be smaller than conventional drip and much less than the potential available soil volume for root growth in most sprinkler or flood irrigated orchards. The smaller wetted soil volume in OH allows greater precision over the supply of nutrients to the crop but at the same time is large enough to provide sufficient anchorage of the crop to avoid uprooting during high wind.

Given that OH will create an environment that encourages the development of a small active root-zone, it is important that the irrigation system is designed and managed to (1) prevent the soil water content declining excessively such that plants are water stressed, (2) minimise leakage of nutrients into waterways, and (3) avoid excessive build up of salt in the root-zone. For example, can an OH system be run for a set duration during the daytime with minimal leakage of nutrients and salt accumulation in the root-zone? Alternatively, what is the impact of OH on nutrient leakage and soil salinity when irrigations are scheduled from a threshold soil water content?

The objective of this study was to simulate water requirements of an OH system applied to a hypothetical citrus orchard. The potential impact on drainage, nutrient leakage and salt accumulation in the root-zone was determined. The practicalities of management for optimum performance of OH under these conditions are discussed.

Materials and Methods

The effects of (i) fixed and (ii) flexible irrigation on soil water content and drainage were simulated over a 12-month period starting 1 January 2004 in a hypothetical OH citrus orchard in Sunraysia by using a 1 h time-step soil water balance model. Fixed irrigation was operated every day for a set duration that was adjusted monthly based on average daily crop evapotranspiration (ET_c). Flexible irrigation was operated when the soil water content declined to a set threshold. ET_c was estimated from a radiation interception model and actual meteorological data. Nitrogen leakage and root-zone accumulation was estimated from a monthly fertigation program (Appendix 1). Accumulation of salt in the root-zone was estimated from the monthly salinity of the water supply.

Soil water balance

A soil water balance (Allen et al., 1998) was used as the base model behind the simulations presented in this report. The approach estimates components of water applied and lost from the crop's root zone from the water balance equation:

$$\mathrm{ET_c + R_{off} + D + SF_{out} = I + R + CR + SF_{in} + \left(SWC_{t\text{-}1} - SWC_t\right)} \qquad \text{(Equation 1)}$$

where ET_c is crop evapotranspiration, R_{off} is surface run off, D is below root-zone drainage, SF_{out} is horizontal sub-surface flow out of the root-zone, I is irrigation applied, R is rainfall, CR is upward flux of water into the root-zone by capillary rise, SF_{in} is horizontal sub-surface flow into the root-zone, SWC_t is the soil water content at time t and SWC_{t-1} is the soil water content at time t-1. All parameters in equation 1 are expressed in units of mm of water.

For the purposes of this study R_{off}, SF_{out}, SF_{in}, and CR were set to zero. In most OH sites SF_{out} and SF_{in} will be minor (unless on steep slopes) and thus can be ignored. Similarly, under drip irrigation on light textured soils R_{off} will be negligible. CR may be an issue at some sites (e.g. perched water table), however, it would be impossible to restrict the size of the wetted root-zone and effectively employ OH in a situation where CR contributed significantly to the supply of water to the tree. Equation 1 was therefore simplified to:

$$\mathrm{ET_c + D = I + R + \left(SWC_{t\text{-}1} - SWC_t\right)} \qquad \text{(Equation 2)}$$

Dynamic simulation of D and SWC_t, at hourly intervals, was undertaken by assuming a constant wetted soil volume that defined root distribution. Initially soil water content was set to the upper limit in the wetted root-zone (SWC_{UL}). When water inputs resulted in the soil water content equalling or exceeding SWC_{UL}, SWC_t was set to SWC_{UL} and D was calculated from:

$$D = I + \left(f_{WZ}R\right) - ET_c + \left(SWC_{t-1} - SWC_{UL}\right) \qquad \text{(Equation 3)}$$

where f_{WZ} was the wetted fraction of soil.

When water inputs resulted in the soil water content remaining below SWC_{UL}, D was set to zero and SWC_t was calculated from:

$$SWC_t = I + \left(f_{WZ}R\right) - ET_c + SWC_{t-1} \qquad \text{(Equation 4)}$$

Average SWC_t in the wetted zone ($WZSWC_t$; cm^3/cm^3) was calculated from:

$$WZSWC_t = \frac{SWC_t}{RZD.f_{WZ}} \qquad \text{(Equation 5)}$$

where RZD was root-zone depth (mm).

Crop evapotranspiration

Diurnal crop evapotranspiration (ET_c) was estimated by the procedure developed for peach (Goodwin et al., 2005):

$$ET_c = 1.1 f\ ET_o \qquad \text{(Equation 6)}$$

where f is the fraction of direct beam solar radiation intercepted by the tree’s foliage and ET_o is reference crop evapotranspiration. f was simulated for the hypothetical citrus orchard from a geometrical light interception model (Goodwin, 2004). Instantaneous estimates of ET_o were calculated from hourly measurements of temperature, humidity, solar radiation and wind speed at Dareton (Allen et al., 1998). Cohen (1991) used a similar approach to compute potential transpiration of grapefruit from the fraction of sunlit leaves.

Soil evaporation was assumed to be negligible and not included in the calculation of ET_c. The combination of a small wetted soil surface in OH and shading of the wetted soil from the tree’s foliage would significantly reduce soil evaporation compared with a sprinkler-irrigated orchard. Bonachela et al. (2001) modelled and measured evaporation from the wetted zones to be 4 to 12 % of orchard water use for a drip irrigated olive orchard in Spain when canopy cover was 36 %. Even lower soil evaporation was predicted with further increases in canopy cover. Similarly, the model of Snyder et al. (2000) predicts low levels of soil evaporation from the wetted zone in Californian peach orchards with high canopy cover.

Rainfall

Hourly rainfall data was sourced from the Bureau of Meteorology weather station at the Mildura airport for the year 2004.

Hypothetical orchard

A hypothetical hedgerow citrus orchard growing in a sandy loam soil was used for simulations. Tree and row spacing were set to 1.8 and 5.0 m, respectively, and row orientation was north-south. Tree cover, defined as the proportion of the soil surface covered by foliage when observed from the vertical, was set to 50 %. Leaf area density was set to a constant 2.5 m^2/m^3 and a spherical leaf angle distribution was assumed. RZD, SWC_{UL} in the wetted root-zone and readily available water (RAW) were set to 550 mm, 41.8 mm and 0.055 cm^3/cm^3, respectively.

The irrigation system consisted of a single drip-line with emitters spaced at 0.6 m having an output of 1.6 l/h. The wetting pattern was described as a 1 m wide strip wetting approximately 20 % of the available soil volume (i.e. $f_{WZ} = 0.2$).

Irrigation scenarios

(i) Fixed irrigation. Irrigation was operated during the daytime for a set duration that was adjusted each month. Irrigation duration was calculated to replace 120 % of average daily ET_c for each month. Irrigation commenced when the midpoint of the required run time coincided with average maximum hourly rate of ET_c.

(ii) Flexible irrigation. Irrigation was automatically operated for one-hour duration. Irrigation was triggered when hourly estimates of $WZSWC_t$ exceeded 10 % RAW. This scenario is equivalent to scheduling irrigation based on hourly measurements of soil water content in the wetted root-zone.

Nitrogen accumulation and leakage

Nitrogen accumulation in the root-zone and leakage below the root-zone were dynamically simulated at hourly intervals using a nitrogen balance model. Application of nitrogen was based on a balanced complete fertiliser program recommended for citrus orchards that varied from month to month. The aim was to annually apply approximately 160 kg/ha nitrogen. Nitrogen was assumed to remain in solution and equilibrate within the wetted root-zone. Best possible practice with respect to matching plant nutrient requirement was compared with 40, 60, 80 and 90 % uptake efficiencies.

Root-zone concentration of nitrogen at time t ($[\mathrm{N}]_t$; mg/l) was calculated from:

$$[\mathrm{N}]_{\mathrm{t}} = [\mathrm{N}]_{\mathrm{t-1}} + \frac{100\left(\mathrm{N}_{\mathrm{applied}} - \frac{\mathrm{N}_{\mathrm{applied}}.\mathrm{N}_{\mathrm{efficiency}}}{100} - \mathrm{N}_{\mathrm{drainage}}\right)}{\mathrm{RZD}.f_{\mathrm{WZ}}.\mathrm{WZSWC}_{\mathrm{t}}} \qquad \text{(Equation 7)}$$

where $[\mathrm{N}]_{\mathrm{t-1}}$ was the root-zone concentration of nitrogen at time t-1 (mg/l), $\mathrm{N}_{\mathrm{applied}}$ was the amount of nitrogen applied (kg/ha), $\mathrm{N}_{\mathrm{drainage}}$ was the amount of nitrogen leaked below the root-zone at time t-1 (kg/ha) and $\mathrm{N}_{\mathrm{efficiency}}$ was the plant uptake efficiency (%). $\mathrm{N}_{\mathrm{applied}}$ at each irrigation was calculated from the recommended monthly total N requirement and estimated daily irrigation requirement. $\mathrm{N}_{\mathrm{drainage}}$ was calculated from:

$$\mathrm{N}_{\mathrm{drainage}} = \frac{\mathrm{D}_{\mathrm{t-1}}[\mathrm{N}]_{\mathrm{t-1}}}{100} \qquad \text{(Equation 8)}$$

Root-zone salinity

Root-zone soil salinity ($\mathrm{EC}_{\mathrm{e(t)}}$; dS/m) at time t was calculated from the total amount of salts applied to a tree (nutrient solution and irrigation source) from:

$$\mathrm{EC}_{\mathrm{e(t)}} = \mathrm{EC}_{\mathrm{e(t-1)}} + \frac{\left(\mathrm{Salt}_{\mathrm{applied}} - \mathrm{Salt}_{\mathrm{drainage}}\right)}{6.\mathrm{RZD}.f_{\mathrm{WZ}}.\mathrm{WZSWC}_{\mathrm{t}}} \qquad \text{(Equation 9)}$$

where $\mathrm{EC}_{\mathrm{e(t-1)}}$ was the root-zone soil salinity at time t-1 (dS/m), $\mathrm{Salt}_{\mathrm{applied}}$ was the amount of salt applied (kg/ha) and $\mathrm{Salt}_{\mathrm{drainage}}$ was the amount of salt in the drainage water at time t-1 (kg/ha). $\mathrm{Salt}_{\mathrm{applied}}$ was calculated from the electrical conductivity of the irrigation source and the nutrient solution, and the amount of irrigation applied. Electrical conductivity of the irrigation source was set to 0.24 dS/m for the months August to October and to 0.3 dS/m for remaining months based on average measurements at Dareton. Electrical conductivity of the nutrient solution varied from a minimum of 0.31 dS/m in July to a maximum of 0.40 dS/m in August, September and October. $\mathrm{Salt}_{\mathrm{drainage}}$ was calculated from:

$$\mathrm{Salt}_{\mathrm{drainage}} = 6.D_{t-1}EC_{e(t-1)} \qquad \text{(Equation 10)}$$

Root-zone EC_e for best possible practice with respect to matching plant nutrient requirement was compared with 40, 60, 80 and 90 % uptake efficiencies.

Leaching irrigation requirements were simulated when root-zone EC_e exceeded the threshold recommended for yield decline in citrus of 1.7 dS/m (Maas, 1990). Leaching irrigation consisted of applying a 12-hour overnight irrigation (excluding nutrients).

Results

Climate, tree water use and applied nitrogen

Total ET_o for the 12-month period was 1723 mm (Table 1). Maximum monthly ET_o occurred in January and minimum was in June. ET_o was 10 times greater than rainfall for the 12-month period. The majority of rainfall occurred in June, July, August, November and December. Total ET_c for the hypothetical orchard over the 12-month period was 1244 mm. The ratio of ET_c to ET_o (i.e. crop coefficient, K_c) for the hypothetical orchard varied from 0.81 to 0.92. Total applied nitrogen was 158 kg/ha. Nitrogen application was minimal during winter but increased in spring. Applied nitrogen ranged from 3 to 24 kg/ha per month.

Table 1. Monthly reference crop evapotranspiration (ET_o), rainfall, estimated crop evapotranspiration (ET_c) and applied nitrogen for a hypothetical OH citrus orchard in Sunraysia. ET_o was calculated from weather data collected at Dareton for year 2004 and rainfall data is from the Mildura airport for year 2004. Applied nitrogen was based on a fertiliser program for citrus orchards.

Month	ET_o (mm)	Rainfall (mm)	ET_c (mm)	Nitrogen applied (kg/ha)
Jan	190	3	155	20
Feb	175	1	145	17
Mar	156	0	133	14
Apr	108	0	95	6
May	66	7	59	4
Jun	45	32	42	3
Jul	50	22	45	3
Aug	84	25	75	10
Sept	97	9	83	16
Oct	165	4	136	23
Nov	160	42	132	20
Dec	179	28	145	24
Total	1723	172	1244	158

Irrigation, Drainage and Nitrogen Leakage

(i) Fixed irrigation

Fixed irrigation ranged from 48 to 182 mm per month (Table 2). This was equivalent to an irrigation duration of 3 h per day in June and July to 11 h per day in December, January and February. Total drainage for the 12-month period was 263 mm with an average irrigation efficiency of approximately 83 %. Total nitrogen leakage for the 12-month period was 0.35 kg/ha.

Table 2. Comparison of monthly applied irrigation, drainage and nitrogen leakage for fixed and flexible irrigation of a hypothetical OH citrus orchard.

Month	Irrigation (mm)		Drainage (mm)		Nitrogen leakage (kg/ha)	
	Fixed	Flexible	Fixed	Flexible	Fixed	Flexible
Jan	182	154	28	0	0.04	0.00
Feb	170	145	25	0	0.03	0.00
Mar	165	133	33	0	0.03	0.00
Apr	112	95	17	0	0.01	0.00
May	66	58	9	0	0.01	0.00
Jun	48	40	14	3	0.01	0.00
Jul	50	43	7	2	0.01	0.00
Aug	83	71	16	3	0.02	0.00
Sept	96	81	15	0	0.03	0.00
Oct	165	135	27	0	0.05	0.00
Nov	160	130	38	6	0.06	0.00
Dec	177	143	34	4	0.06	0.00
Total	1474	1228	263	19	0.35	0.00

Changes in $WZSWC_t$ for the 12-month period are shown in Figure 1a. $WZSWC_t$ was lower than 10 % of RAW on 257 days but only exceeded RAW on 5 days. Driest periods were during winter and spring. Diurnal changes in $WZSWC_t$ for a ten-day period from 1 January are shown in Figure 1b. Generally, $WZSWC_t$ was lower than 10 % RAW in the evening and during the night-time after irrigation had ceased and in the morning before irrigation commenced.

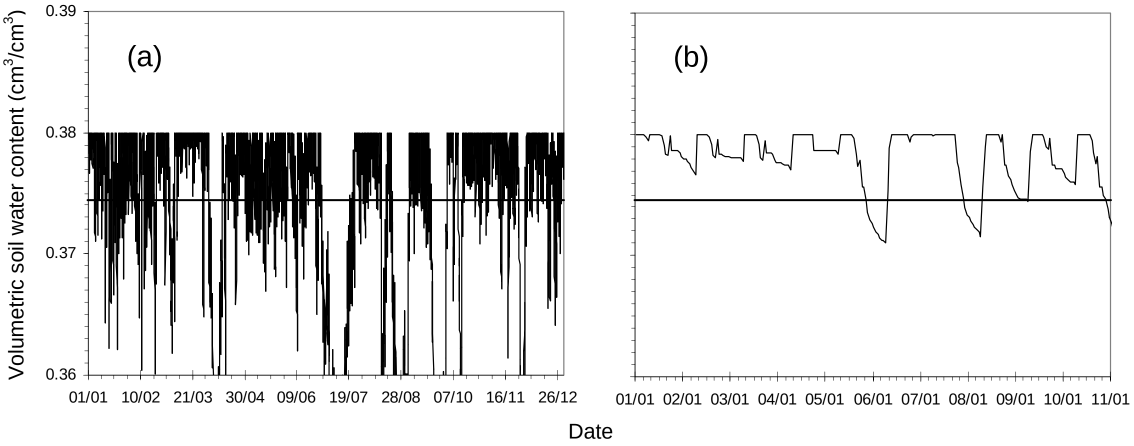

Figure 1. Changes in average volumetric soil water content in the wetted zone under fixed irrigation for (a) 12-months, and (b) 10 days in January. Upper limit soil water content in the wetted zone was set to 0.38 cm^3/cm^3. Horizontal line indicates 10 % of readily available water.

(ii) Flexible irrigation

Total irrigation over the 12-month period was 1228 mm with an irrigation efficiency approaching 100 % (Table 1). Irrigation was applied on 364 days. The 2 days when irrigation was not applied corresponded to winter rain during the daytime. Drainage was 19 mm and corresponded to rainfall events. There was no leakage of nitrogen.

Changes in $WZSWC_t$ for the 12-month period are shown in Figure 2a. Minimum $WZSWC_t$ was 0.366 cm^3/cm^3 corresponding to 26 % of RAW. Diurnal changes in $WZSWC_t$ for a ten-day period from 1 January are shown in Figure 2b. Irrigation was close to non-stop during the daytime when ET_c was high (e.g. 1 January). In contrast, when ET_c was low (e.g. 4 January), irrigation was applied several times during the daytime (i.e. pulses).

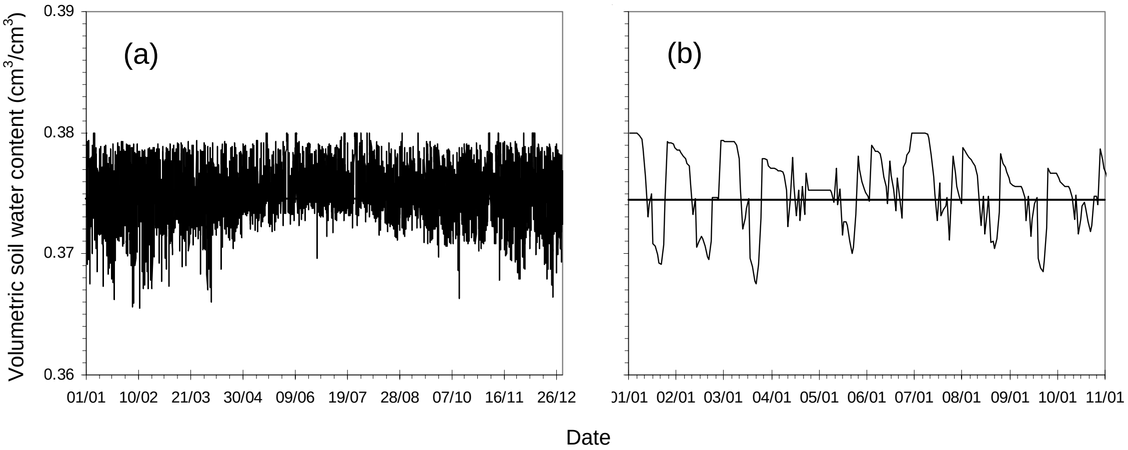

Figure 2. Changes in average volumetric soil water content in the wetted zone under flexible irrigation for (a) 12-months, and (b) 10 days in January. Upper limit soil water content in the wetted zone was set to 0.38 cm^3/cm^3. Horizontal line indicates 10 % of readily available water.

(iii) Sensitivity to changes in ET$_c$

Decreasing ET$_c$ resulted in an increase in drainage and nitrogen leakage under fixed irrigation due to applied irrigation remaining constant (Table 3). Under flexible irrigation, drainage was maintained at approximately 20 mm and nitrogen leakage was negligible.

Table 3. Effects of decreasing crop evapotranspiration (ET$_c$) on applied irrigation, drainage and nitrogen leakage over the 12-month period for fixed and flexible irrigation of a hypothetical OH citrus orchard.

ET$_c$ (mm)	Irrigation (mm)		Drainage (mm)		Nitrogen leakage (kg/ha)	
	Fixed	Flexible	Fixed	Flexible	Fixed	Flexible
1244	1474	1228	263	19	0.35	0.00
1120	1474	1103	388	18	0.58	0.00
995	1474	980	512	19	0.86	0.00
871	1474	855	637	19	1.23	0.01
747	1474	732	761	20	1.71	0.01
622	1474	607	886	20	2.40	0.01

Table 4 shows the effects of increasing ET$_c$ on applied irrigation and soil water content. Irrigation remained constant under fixed irrigation but increased in proportion to the increase in ET$_c$ under flexible irrigation. Average WZSWC$_t$ over the 12-month period under fixed irrigation decreased to less than RAW when ET$_c$ increased by 20 %. By contrast, average WZSWC$_t$ under flexible irrigation was maintained above 0.37 cm^3/cm^3. Minimum WZSWC$_t$ was substantially less under fixed irrigation compared with flexible irrigation. Minimum $WZSWC_t$ under flexible irrigation was maintained within RAW as ET_c increased up to 50 %.

Table 4. Effects of increasing crop evapotranspiration (ET_c) on applied irrigation, and the average and minimum wetted zone soil water content ($WZSWC_t$) over the 12-month period for fixed and flexible irrigation of a hypothetical OH citrus orchard.

ET_c (mm)	Irrigation (mm)		Average $WZSWC_t$ (cm^3/cm^3)		Minimum $WZSWC_t$ (cm^3/cm^3)	
	Fixed	Flexible	Fixed	Flexible	Fixed	Flexible
1244	1474	1228	0.373	0.376	0.317	0.366
1392	1474	1369	0.361	0.375	0.284	0.358
1540	1474	1493	0.286	0.375	0.187	0.354
1687	1474	1601	0.000	0.375	0.000	0.352
1835	1474	1742	0.000	0.374	0.000	0.346
1982	1474	1867	0.000	0.374	0.000	0.343

Nitrogen Accumulation in the Root-zone

Total nitrogen applied to the hypothetical orchard was 158 kg/ha (Table 1). Figure 3 shows the effects of tree uptake efficiency on $[N]_t$ under fixed and flexible irrigation. The $[N]_t$ was much greater under flexible than fixed irrigation when the uptake efficiency was less than 100 %. The rate of nitrogen accumulation was greatest during spring and summer corresponding to the greatest application rate. Over the 12-month period, at 40 % uptake efficiency, $[N]_t$ was 45 and 176 mg/l under fixed and flexible irrigation, respectively. Given that 85 % of nitrogen was applied as nitrate, then this was equivalent to 55 and 211 kg/ha nitrate in the root-zone under fixed and flexible irrigation, respectively.

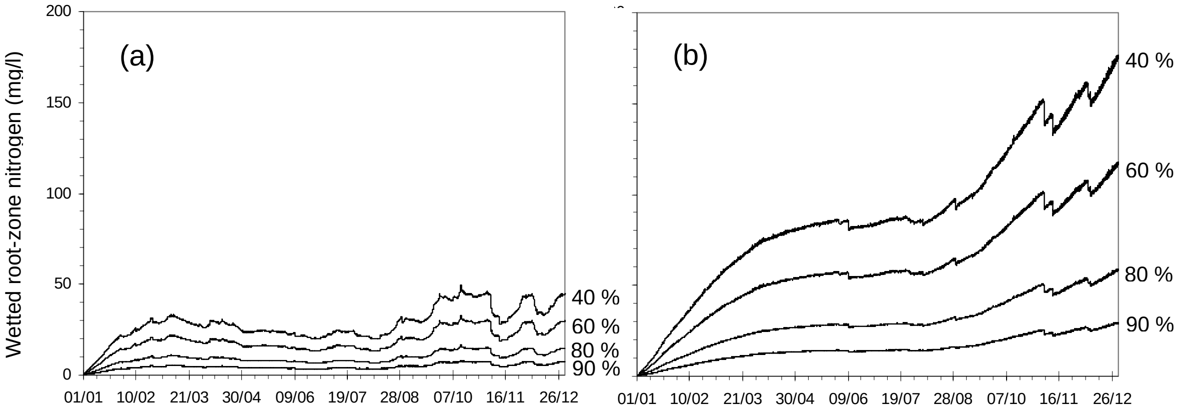

Figure 3. Root-zone nitrogen concentration (at the upper limit of soil water content) over a 12-month period at tree uptake efficiencies of 90, 80, 60 and 40 % under (a) fixed irrigation and (b) flexible irrigation. Total annual application of nitrogen was 158 kg/ha.

The effects of uptake efficiency on nitrogen leakage are shown in Table 5. Nitrogen leakage increased from 0.35 kg/ha at 100 % uptake efficiency to 76.4 kg/ha at 40 % uptake efficiency under fixed irrigation. Similarly, nitrogen leakage increased under flexible irrigation to 22.5 kg/ha at 40 % uptake efficiency.

Table 5. Effects of on nitrogen leakage over the 12-month period for fixed and flexible irrigation of a hypothetical OH citrus orchard.

Uptake efficiency (%)	Fixed	Flexible
100	0.4	0.0
90	12.8	3.8
80	25.5	7.5
60	51.0	15.0
40	76.4	22.5

Root-zone Salinity

Root-zone EC_e was maintained close to the threshold for yield decline in citrus under fixed irrigation at a nutrient uptake efficiency = 100 % (Fig. 4). By contrast, under flexible irrigation, root-zone EC_e exceeded the threshold by mid-February and continued to increase up to 6.3 dS/m over the 12-month period. Under fixed irrigation, root-zone EC_e was maintained over the 12-month period at approximately 1.9, 2.1, 2.3 and 2.6 dS/m whereas under flexible irrigation root-zone EC_e continually increased over the 12-month period to 7.1, 7.9, 9.6 and 11.2 dS/m at nutrient uptake efficiencies of 90, 80, 60 and 40 %, respectively.

Leaching irrigations were required under flexible irrigation at all levels of nutrient uptake efficiency. At 100 % uptake efficiency, 35 leaching irrigations contributed 191 mm to drainage over the 12-month period (Fig. 5).

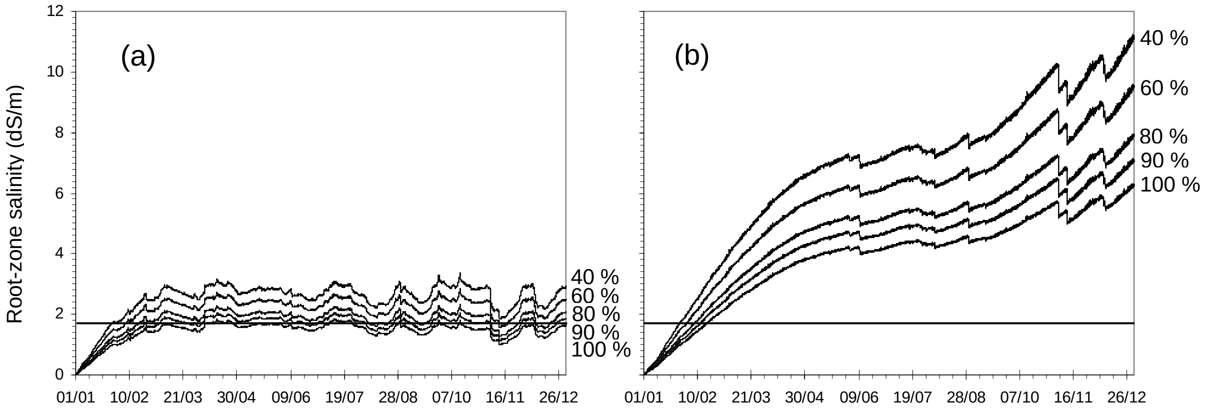

Figure 4. Root-zone salinity over the 12-month period at tree nutrient uptake efficiencies of 100, 90, 80, 60 and 40 % under (a) fixed irrigation and (b) flexible irrigation. Irrigation water electrical conductivity was set to 0.24 dS/m for the months of August to October and 0.30 dS/m for all other months. Horizontal line indicates EC_e threshold for yield decline in citrus.

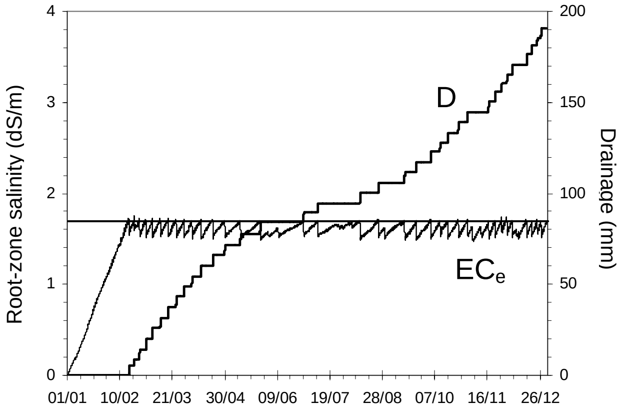

Figure 5. The effects of leaching irrigations on root-zone salinity (EC_e) and drainage (D) over the 12-month period under flexible irrigation. Leaching irrigations were applied overnight for 12 h using nutrient less water. Horizontal line indicates EC_e threshold for yield decline in citrus.

Discussion

The results of this simulation study showed that both drainage and nitrogen leakage were higher under fixed compared with flexible OH irrigation. Under fixed irrigation, approximately 18 % of applied irrigation ended up below the root-zone, potentially taking with it just 0.2 % of the applied nitrogen (assuming 100 % plant uptake efficiency). Soil water content was drier than 10 % of RAW on most days although this occurred predominantly in winter and spring, and during the night or early morning in summer. Soil water content was rarely drier than RAW. Irrigation run time and start time for each month remained constant and were based on average daily ET_c and the time of maximum ET_c. Such an approach to estimate irrigation requirement is simple and could be further improved by using a fortnightly rather than monthly average daily ET_c.

Under flexible irrigation, drainage and leakage were negligible. Soil water content was often drier than 10 % of RAW but never exceeded 26 % of RAW. This was attributed to the time-step used in this simulation study being restricted to 1 h by the weather data. In practice, irrigation could be scheduled more frequently by measuring soil water content at a shorter time interval.

Drainage, nitrogen leakage and soil water content were sensitive under fixed irrigation to inaccurate estimates of ET_c. Over 60 % of applied irrigation ended up as drainage when estimates of ET_c were 50 % greater than actual ET_c. Nitrogen leakage remained relatively low at 1.5 % of applied nitrogen. When estimates of ET_c were lower than actual ET_c, the root-zone dried out rapidly. These results suggest that accurate estimates of ET_c are essential to avoid drainage and tree water stress. In contrast, drainage and nitrogen leakage were insensitive to ET_c under flexible irrigation. Soil water content, however, declined and this was attributed to the limitation of the irrigation system to apply sufficient water to meet ET_c. In other words, on days when ET_o was high, irrigation was run non-stop during the daytime but this was not enough water to stop the trees decreasing available soil moisture supplies. This highlights the importance of designing an irrigation system so that the application rate is greater than the rate of water extraction by the trees.

Flexible OH irrigation has the capability of containing drainage and nutrients but there is still a risk of nutrient build-up in the wetted zone (at less than 100 % nutrient uptake efficiency) that is susceptible to leakage from rainfall events. The amount of nitrogen accumulated in the wetted zone under flexible irrigation depended on tree uptake. Even at 90 % uptake efficiency, the concentration of nitrogen after 12-months reached 29 mg/l. This is equivalent to a potential loss of 35 kg/ha of nitrate below the root-zone. Large rainfall events (i.e. greater than those measured in 2004) could readily leach this pool of nitrate past the root-zone.

The sensitivity of nitrogen leakage and accumulation to nutrient uptake efficiency highlights the need to match nitrogen applied to crop removal. Further studies are required to understand the dynamics of nutrient uptake and the impacts of nutrition on fruit yield and quality. Management should aim to drive productivity by careful regulation of nutrition.

Both root depth and the extent of the wetted zone will influence drainage, nutrient leakage and the rate of soil drying. Root depth was assumed constant at 0.55 m in this study. Syvertsen and Lloyd (1995) cited several studies that showed the fibrous root-zone in citrus was above 0.5 m depth irrespective of soil type and citrus roots concentrate in the wetted zone. Total root depth may be greater. Allen et al. (1998) reported maximum root depth in citrus to range from 0.8 to 1.5 m depending on tree size. These deeper roots may have the capacity to mop up at least some of the nutrients leached below the fibrous root-zone.

The horizontal extent of the wetted zone was also assumed constant in these simulations. Based on the model WetUp (CSIRO, 2005) the width of the wetting pattern will vary depending on the duration of irrigation. This increase, however, does not consider concurrent soil drying during the daytime from root water extraction. For the purposes of this study the assumed constant wetted zone was sufficient but it should be noted that drainage, leakage and $WZSWC_t$ will be influenced by the size of the wetting pattern and henceforth the size of the root-zone.

Rainfall contributed very little to drainage and nitrogen leakage in this simulation study. The effect of rainfall on drainage, nitrogen leakage and $WZSWC_t$ depends on the intensity, timing and duration of each rainfall event. For example, there was approximately 3 mm of water held between 10 % RAW and $WZSWC_{UL}$ in the hypothetical orchard. Therefore a maximum of 3 mm rainfall can be captured. During the daytime, soil water from such a rainfall event is rapidly depleted by ET_c because of the confined root-zone. Hence, daytime rainfall contributed little to drainage and leakage compared with night-time rainfall. In practice, delaying irrigation events is difficult and reliance must be placed on measurements of soil water content.

OH, like any other irrigation system, requires a leaching fraction to remove salts that accumulate in the root-zone. In this simulation study there was sufficient leaching under fixed irrigation to maintain root-zone EC_e at approximately 1.7 dS/m. In contrast, a rapid increase in root-zone EC_e was simulated under flexible irrigation. EC_e reached threshold levels for yield decline in citrus within two months and this time frame decreased to less than one month when nutrient uptake efficiency was 40

%. Rainfall was insufficient to leach salts out of the root-zone. Reliance on rainfall to leach salts is therefore not recommended and a leaching fraction must be incorporated into irrigation events. It should also be noted that these results would change with irrigation water salinity levels. Values recorded at Dareton of 0.24 to 0.3 dS/m were used but these could be substantially higher in other irrigation districts.

Leaching was simulated for flexible irrigation. This required 192 mm of additional irrigation most of which was drainage. No nitrogen leakage occurred because leaching irrigation was nutrient free however if nutrient uptake was less than 100 % then significant nitrate would be leached.

The simulated leaching fraction for the 12-month period was approximately 0.15. Using the equation recommended by Ayers and Wescot (1985) the leaching fraction necessary to maintain EC_e = 1.7 dS/m using an average irrigation water salinity of 0.29 dS/m is 0.04. The main difference is that Ayers and Wescot (1985) used a gradation in root concentration and water uptake with soil depth. Root density was assumed constant throughout the wetted zone in the present study. In practice, leaching fraction should be based on field measurements of root-zone EC_e.

Field measurements of nitrate concentration in the soil solution at different depths in conventional fertilised citrus orchards are variable. Dale and McClure (1994) showed that in one citrus orchard, irrigated by under-tree minisprinklers, a single application of 100 kg/ha N as ammonium nitrate resulted in a steady increase over the season in the concentration of nitrate below the root-zone. Nitrate concentration at 0.6 m depth was approximately 80 mg/l after 8 irrigations (20 weeks later). However, in other orchards where similar amounts of nitrogen fertiliser were applied, nitrate concentrations below the root-zone were negligible. More recent field measurements of soil solution nitrate concentration at 0.5 m depth in a sprinkler irrigated citrus orchard has shown levels above those predicted in this OH study (Falivene, unpublised). Nitrate concentration reached 450 mg/l in early February following the application of 22 kg/ha N as urea in mid January and then declined to approximately 100 mg/l by mid February suggesting substantial loss of nitrate below the root-zone. Measurements of soil solution electrical conductivity at the same site revealed that total dissolved salts in the mid root-zone and at 0.5 m remained below 1.0 dS/m for the period January to April.

Conclusion

Simulations of water and nutrient application using an OH system applied to a hypothetical citrus orchard highlighted the need for good management and appropriate irrigation design. Matching irrigation to ET_c is needed so that drainage is minimised and periods of water stress are avoided. An OH orchard triggered to irrigate when the soil water content reached a threshold appeared to have advantages because the frequency of irrigation are automatically altered according to the depletion of soil water. Alternatively, irrigation events could be triggered based on continuous computations of ET_o. Such an approach requires accurate estimates of ET_c, wetted volume of soil and RAW. In practice, irrigation triggered by soil water content or ET_c requires sophisticated management. A system that combines an estimate of ET_c and measurements of soil water content with appropriate feedback systems (i.e. monitoring of plant water stress, salt accumulation and drainage) would be ideal. According to this study, under the conditions simulated here, such a system will optimise irrigation efficiency while substantially reducing loss of nitrogen. Studies to validate this model in a real citrus orchard are recommended.

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Appendix 1 – Monthly fertiliser program

Table 6. Total monthly application of nitrogen, potassium, phosphorous, calcium and magnesium used the simulation study.

Month	Crop growth stage	Nitrogen (kg/ha)	Potassium (kg/ha)	Phosphorous (kg/ha)	Calcium (kg/ha)	Magnesium (kg/ha)
Jan	Cell expansion	19.9	24.3	4.7	21.7	19.7
Feb	Cell expansion	17.0	20.7	4.0	18.5	16.8
Mar	Cell expansion	13.1	16.0	3.1	14.3	13.0
Apr	Maturation	5.7	9.2	1.6	4.8	6.6
May	Maturation	4.1	6.6	1.2	3.4	4.8
Jun	Maturation	2.8	4.5	0.8	2.3	3.2
Jul	Dormancy	3.8	3.5	0.6	3.3	4.2
Aug	Activation	11.3	7.7	1.3	5.3	6.7
Sept	Activation	16.4	11.1	2.0	7.8	9.7
Oct	Activation	22.3	15.2	2.7	10.6	13.3
Nov	Cell division	19.9	9.6	8.1	21.6	8.2
Dec	Cell division	23.9	11.6	9.7	25.9	9.8
Total		160	140	40	139	116

Table 7. Annual application of each fertiliser used the simulation study.

Fertiliser	Annual application (kg/ha)
Potassium Nitrate	172
Potassium Sulphate	149
MAP	111
Ammonium Nitrate	20
Magnesium Nitrate	126
Calcium nitrate	454
Magnesium Sulphate	303
Phosphoric acid (81%, L)	36
Sulphuric acid (11%, L)	849

Please note: This is an example of an OH nutrition program for a mature citrus orchard. The program should not be considered as a recommendation. OH nutrition programs are developed to suite site conditions (yield, variety, soil, climate, water quality etc). Duplicating this or any other nutrition program for your orchard may result in negative impacts on productivity and returns.