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Aerated water irrigation (oxygation) benefits to pineapple yield, water use efficiency and crop health

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Key words: *Ananas comosus*, CAM photosynthesis, 'D' leaf, *Phytophthora,* root respiration.

Abstract: Pineapple roots need adequate oxygen to function, sustaining growth and yield. The crop is susceptible to soil saturation caused by natural rainfall or irrigation, or even with drip irrigation that creates sustained wetting fronts. Drip and subsurface drip irrigation can develop sustained wetting fronts, particularly in low permeability soils, predisposing plant roots to a low oxygen environment. We evaluated the use of aerated irrigation water "oxygation", employing Mazzei air injectors which mix air with irrigation (12% air by volume of water) in-line, increasing oxygen concentration in the irrigation water stream. The effect of this treatment was evident in growth, development, and leaf gas exchange parameters. Total fruit yield increased by 44 and 26% whereas industry yield increased by 11 and 6% due to oxygation compared to the control and no irrigation, respectively. High yield was associated with an increase in fruit size and not the number of fruits produced. *Phytophthora* infestation in the oxygation (3% of plants) was significantly reduced compared to the control (4.9%), and without irrigation treatment (10.5%) suggesting that reasonable management of *Phytophthora,* which is one of the major pathological problems for pineapple production in Australia and elsewhere, can be addressed through aerated water irrigation. Oxygation responses were mediated through root and soil processes involving greater root biomass, root respiration, increased microbial diversity and enhanced soil aeration status.

1. Introduction

World production of pineapple (*Ananas comosus* L.) reached 19 million tonnes in 2008 with the industry dominated by Brazil followed by Thailand, the Philippines and Indonesia. In Australia, pineapple, as an exotic species, is grown almost exclusively in Queensland, producing 104,000 tonnes annually with an industry average yield of 37.9 t ha^{-1} in ~2700 ha (Dhungel *et al.*, 2009) contributing an annual farm gate value of Au$50 million (FAO, 2011). Thanks to Crassulacean acid metabolism (CAM), pineapple is adapted to dry environments. However, pineapple is sensitive to water-logging and therefore requires a well-drained soil with good aeration when grown with irrigation. Pineapple response to irrigation is generally high for yield and quality.

Industry interest in developing irrigation for pineapple has been triggered by recurring episodes of drought brought about by climate change, and a major shift in the historical rainfall pattern, and under such circumstances strategic and supplementary drip irrigation are imperative for a sustainable industry (Camp *et al*., 1993). Increased cost of water, reduced ground water reserves and vocal public pressure have forced growers to look for more effective alternatives to the traditional surface flood and furrow irrigation. In response, increasing adoption of localized micro irrigation such as sprinkler, drip irrigation (DI) or subsurface drip irrigation (SDI) is taking place to improve water use efficiency (WUE) and to minimize environmental impacts by reducing runoff and deep drainage (Thompson *et al*., 2002).

The irrigation efficiency of sprinkler systems is less than for drip systems due to evaporative losses and the tendency to promote foliar diseases in the former. Although far more efficient, DI and SDI can induce temporal hypoxic conditions in the rhizosphere due to their sustained wetting fronts, particularly in fine textured soil (Machado *et al*., 2003) where oxygen may not be sufficiently available for root respiration. Localized water-logging purges the soil pores of air and causes hypoxia, reducing root metabolic activity and function (Goorahoo *et al.,* 2002; Bhattarai and Midmore, 2009). Alleviation of hypoxic rhizosphere conditions can be achieved through the use of aerated water for irrigation, increasing oxygen availability in the root zone (Su and Midmore 2006; Dogan *et al.*, 2008). Oxygation, the term we use for aerated irrigation water with SDI, has been shown to benefit growth of a range of crops, particularly in heavier soils. This is because even under normal irrigations, roots can suffer due to a lack of soil oxygen. An increase in crop yields and WUE has been

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confirmed by Bhattarai *et al.* (2004) with the use of aerated water irrigation in a number of annual crops with C_3 metabolism. Other studies on other crops in a range of soil types with drip and SDI have also been implicated in creating a wetting front that can induce the possibility of hypoxia in the rhizosphere (Goorahoo *et al*., 2002; Midmore *et al.*, 2006).

Drip irrigation which involves point source water application in the rhizosphere could lead to constantly poor aeration around the root zone and predispose pineapple plants to a number of physiological disorders and susceptibility to *Phytophthora* root rot. Oxygation, using aerated water that has potential to ameliorate the hypoxic/ anoxic conditions, may be of benefit not only to improve the WUE, yield and quality but also to minimize disease caused by *Phytophthora,* with symptoms of root and fruit rot in pineapple. Previous research in annual crops has demonstrated the potential of oxygation to improve yield and WUE (Bhattarai and Midmore, 2009).

Most of the effects of water-logging in pineapple are mediated through the roots, including predisposition of the root system to a number of diseases including root and fruit rot. Generally field grown pineapples tend to develop roots in the upper soil layer, where they are confined and follow the wetting area. As the root activities are bound to the wetting fronts, the susceptibility to *Phytophthora* is generally high. Recent adoption of drip irrigation for pineapple in Australia and elsewhere is encouraging. Introduction of aerated drip systems can be pivotal in improving irrigation water use efficiency and minimising the infestation by *Phytophthora* in pineapple. The main objective of this trial was to determine under what conditions there is a measurable positive effect of aeration and how that relates to impact upon incidence of *Phytophthora* and on general crop growth and development. The study was designed to evaluate the effectiveness of oxygation in a perennial crop - pineapple - with the CAM pathway for carbon fixation, evaluating the benefits on fruit yield, quality, and water use efficiency. We report the results of field research carried out in collaboration with Valley Syndicate Pineapple Farm in Yeppoon, QLD Australia from 2007 to 2011 in order to evaluate the above mentioned effects of aerated water for drip irrigation.

2. Materials and Methods

Trial site and soil

The field experiment was conducted at Valley Syndicate Pineapple Farm, Yeppoon, Central Queensland, Australia (23°9'31.12°S, 150°42'51.36°E). The crop was grown over the period 2007-2011 from which two harvests were taken as main crop and first ratoon crop. Total area of the experimental site was 2.15 ha on a calcareous sandy loam soil, with organic carbon 0.68-1.2%, total nitrogen 0.06-0.09%, potassium (Colwell) 25-139 mg/kg, and phosphorus (Colwell) content of 18-39 mg/kg. The crop seasons were relatively wet compared to long-term averages. The region is described as a semiarid tropical environment, with summer-dominant rainfall (Fig. 1).

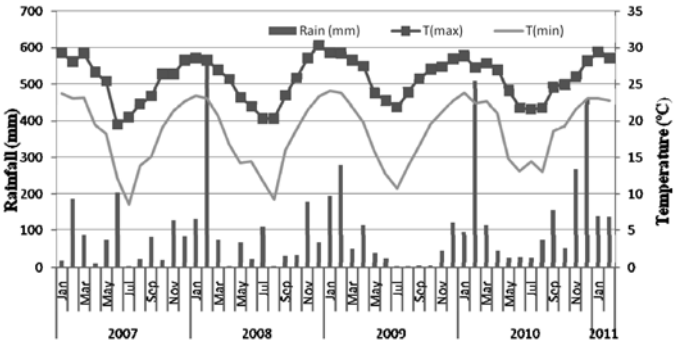

Fig. 1 - Total monthly rainfall (mm), monthly average maximum temperature (°C), and monthly minimum temperature (°C) over the experimental period at Yeppoon.

Experimental design

The experiment was a randomised block design, with two SDI irrigation treatments, with and without oxygation. Air injection into the irrigation water for oxygation was supplied by a 1583™ air injector venturi (Mazzei Corp, USA) installed in-line immediately before the field plot, regulated to ingress 12% air by volume of water following Bhattarai *et al.* (2006). The experiment was replicated seven times within 14 field plots (average dimensions 16 m x 70 m) where seven plots received aerated water by SDI and seven plots were irrigated without aerated water. An adjacent block, comprising three plots, received no irrigation (although all other inputs such as fertilizer, flowering regulation chemicals, fungicides and insecticides were identical) and was included as a third treatment (no-irrigation) for comparison purposes.

Planting materials and crop management

Crowns of pineapple variety GC1 were planted on 24 October 2007, in a double row, raised bed (10 cm high) system to accommodate up to 53,333 plants/ha. Inter row space was 50 cm and between plants was 25 cm, whereas centre to centre between the bed was maintained at 1.5 m. The oxygation treatment commenced 14 March 2008 (139 days after planting). Ethylene (ethephon) was applied twice as a saturated solution in water and activated charcoal to enhance absorption to induce flowering, as pressurized spray late in the evening or at night for enhanced uptake through the stomata. Plants were of an optimum size (~2 kg) for forcing in order to obtain even flowering.

Irrigation design and scheduling

Irrigation was blocked in four units. A Mazzei air injector was installed near the block (3 m from the first plot), whereas the pump was installed near to reservoir about 1 km distance from the plot. The inlet pressure of 45 PSI was achieved at the point of the Mazzei air injector installation. A pressure differential across the air injector was maintained at 45 and 15 PSI for the inlet and outlet, respectively, to maintain air injection at 12% by volume

of water (Fig. 2). The drip tube (manufactured by Plastro Australia) consisted of pressure compensated emitters at 30 cm intervals emitting at the rate of 1.2 l/hr, buried at 150 mm from the soil surface, one drip tube per bed running between two 50-80 m length crop rows.

Fig. 2 - Mazzei air injector installed in a pressurised irrigation line close to the plot for air injection into irrigation water for oxygation (top), and the first year crop at fruit development stage (b) being marked for destructive sampling.

Irrigation and soil water monitoring

Soil water content was monitored at depths of 10, 20, 30 and 40 cm, logged at 15 min intervals but averaged daily, using a calibrated Odyssey GreenLight-RedLight™ (GLRL) sensor (capacitance probes manufactured by Data Flow System Pvt Ltd, NZ). There was one monitoring site in each plot. Soil moisture was also measured (at 10 cm intervals from 10-60 cm depths) during the diurnal measurement of photosynthesis over a period of five days in January 2010; a calibrated Odyssey Micro-Gopher system, the probe of which consists of a capacitance sensor (Soil Moisture Technology, Australia) was used. Scheduling of irrigation was based on the averaged readings from the GLRL sensors at 20 cm depth; the amount applied was calculated to take soil moisture content when at C. <50% of the field capacity (FC 36 mm H_2O per 100 mm soil depth) to refill the soil water reservoir by irrigation to reach field capacity. This required different durations to bring the soil to FC.

Water applied to individual blocks (oxygation and control) was measured with two calibrated water meters installed near the pumping station and the rainfall data were accessed from a nearby weather station (<1 km aerial distance).

Nutrients to the crop were supplied through an industry standard rate of basal application of macro and micro nutrients and top dressing by spreading in the non-irrigated plot and by fertigation on drip irrigated plots supplied at the equivalent dose for all treatments. The industry strategies for increasing pineapple yield and fruit size included side dressing of nitrogen (160 k/ha), phosphorus (60 kg/ha) and potassium (193 kg/ha) over five split applications in a year. An additional dose of magnesium (12 kg/ha) was also applied once.

Soil oxygen monitoring

The O_2 concentration in the soil was measured at 15 cm depth between two emitters and offset 5 cm from the drip tube using PSt3 O_2 sensitive Fibre-optic minisensors with fibox-3 oxygen meters (PreSens GmbH, Germany) as described by Klimant *et al.* (1995). Sensors were installed in the soil for five days prior to data collection and soil oxygen monitoring took place for two days before oxygation, during oxygation and two days post oxygation event in the oxygation and control plots following the procedure of Chen *et al.* (2010). Soil oxygen monitoring was also performed in the ratoon crop over the period of four days before (-48 hr), during (0 h) and post (+48 hr) irrigation.

Destructive plant sampling for dry matter partitioning

Destructive plant sampling for dry matter accumulation and partitioning was carried out on 22 Nov 2008 (392 DAT) and 15 January 2010 (713 DAT) to evaluate the treatment effects in the main and ratoon crops. Plant samples collected from two whole 2 m linear lengths per bed were separated into leaf, stem, fruits and roots, oven-dried at 70°C, and the fresh and dry weights of each component were recorded. The 'D' leaf is always easy to pull from the plant and has leaf margins that are more-or-less parallel all the way to the leaf base (Bartholomew, 2008). The 'D' leaf is defined as the youngest physiologically mature leaf on the plant and also is the tallest leaf on the plant. Plant height and SLA were measured on the 'D'leaf.

Diurnal changes in gas exchange and plant parameters

Light interception by the canopy was measured using an AccuPAR Ceptometer (Decagon, USA) and canopy temperature was recorded using an Everest AG Multimeter. Leaf photosynthesis (A), transpiration (E) and stomatal conductance (SC) were measured at 6 hr intervals using an Infrared Gas Analyser (IRGA) LCA-4 (ADC, UK) on two fully-expanded topmost sunlit leaves per plot on each occasion at early morning (dawn), midday, dusk and at night following Adams *et al.* (2002). Soil respiration was

measured in the soil 3-5 cm from the plant using IRGA principle with an EGM-3 (PP Systems (UK) following Hanson *et al.* (2000) on 392 DAT for the main crop and 713 DAT for the ratoon crop. Data collection was also carried out to measure the gas exchange responses of the crop before, during and after oxygation events in the aerated SDI, the control SDI and no irrigation treatments. Pre-irrigation data were collected over a 24 hr period, on 14-15 January 2010 at 6 hr intervals to include dawn, midday, dusk/early evening and night to determine diurnal patterns of leaf gas exchange parameters during and post irrigation, and data on soil moisture and soil respiration were also collected using Microgoopher and EGM-3 soil respiration systems, respectively.

Harvesting and yield determination

Harvesting was performed at two scales, i.e. sample plot harvesting for total yield and industry harvest for marketable fruits yield. For sample plot harvests, all fruits were hand-picked at maturity from two rows of 2 m linear lengths (16 plants) selected from each of the seven replicated bordered plots, and from three plots in the non-irrigated area. The fruits were counted, weighted and processed for quality parameters for both main crop and ratoon crop. Change in fruit colour, particularly to the eye, from green to yellowish was considered an index for maturity and harvesting. Fruits without crown and peduncle were weighed. The industry harvest represents only marketable fruit yield harvested by the crew of pickers in a mobile harvester. Commercially-harvested fruits were weighted in the load cells with wooden crates containing ~500 kg. Commercial harvest was carried out for each plot separately at approximately weekly intervals. The main crop was harvested from January to April 2009 and it was left for ratoon which recommenced harvesting in 2010. The ratoon crop was harvested 28 June to 11 October 2010, and the whole crop was then uprooted for planting of a new crop, hence the crop spanned a period of 39 months from planting.

Fruit quality determination

Mature fruits harvested from sample areas were used for quality determination. Fruit quality parameters measured included °brix, fruit size, volume, density, fruit height and width, flesh colour, skin colour, dry matter, translucency and flavour, following the standard analytical method described by Bartolome *et al.* (1995). Fruit quality was assessed on fruits from different harvests in the main and also in the ratoon crop. In total, 20-50 randomly selected mature fruits were assessed for quality in the main and ratoon crops. The flavor score was determined based on smell by a panel group following industry standard; 1= no flavor, 2= little flavor, 3= good flavor.

Water use efficiency

Crop water use efficiency was calculated to represent irrigation water use efficiency (IWUE) and gross water use efficiency (GWUE). IWUE is calculated as fruit yield (t) per megaliter of irrigation input, whereas GWUE is the fruit yield (t) per megaliter of crop water input, comprising both the inputs from irrigation and rainfall. Instantaneous water use efficiency (WUE_i) was calculated from the IRGA data which represent μmol CO_2 assimilated for each mmol of H_2O transpired during measurement of the photosynthesis process.

Soil physical and chemical parameters

Changes in soil physical and chemical properties were assessed by measuring soil compaction, bulk density and air filled porosity (following the method of USDA, 2010) and soil organic carbon (Kuhlbusch, 1995) and nitrogen (ISO 13878 Soil quality - elemental analysis). Soil compaction was determined with Remek CP4011 soil cone penetrometers (ICT international, Australia) during the destructive plant sampling period to a depth of 35 cm from the soil surface. Soil water samples were collected at 50 cm depth for sub-surface leaching and nutrient analysis particularly nitrate signature using wetting front detectors (CSIRO, Australia). Subsurface solution samples were also collected from ceramic solusamplers placed at depths of 20 cm and 50 cm to determine nutrient transfer through the soil profile. At the end of the crop season, soil cores (20 cm deep and 8.6 cm diameter) were collected to determine bulk density, root density, air filled porosity at field saturation, field capacity and in dry soil following the method by Peverill *et al.* (2002).

Soil microbial and phytophthora determinations

Fluorescein diacetate hydrolysis activity (FDA) analysis provides a surrogate measure of the soil microbial load. Soil samples were collected during harvest at the depth 10 cm and 10 cm distance from emitter, and were used for FDA analysis following the method described by Adam and Duncan (2001). The incidence of *Phytophthora* infestation was assessed in the field crop. In each plot, a double row comprising ~500 plants was examined for infestation based on the visual symptoms following Pegg (1977). Plants with characteristic symptoms of *Phytophthora* on fruit and crown rot were counted and percentage infestation calculated.

Data analysis

Data were analysed following the procedures for analysis of variance (ANOVA) for randomised block design in GenStat Version 11 (VSN International, UK) as the no irrigation plots were contiguous to SDI plots. For most of the crop, only the main effects of soil and water parameters are presented, whereas for all other data collected during the diurnal events (leaf and soil gas exchange parameter) the effects of the treatment on the diurnal course were also analysed. Hence some significant interactions between the treatments and diurnal effects have been analysed and presented. Means were separated by the least significant difference (LSD) at $P \leq 0.05$.

3. Results and Discussion

Weather conditions

Rainfall was recorded as 917 mm, 1294 mm, 875 mm, and 1850 mm for 2007, 2008, 2009 and 2010, respective-

ly (Fig. 1). 2010 had the highest rainfall, more than four times that of the driest years in the past 20 years. Total rainfall input during the entire crop period was 4250 mm.

Irrigation input

Irrigation scheduling was based on measurement of the soil moisture deficit. The same delivery system through Mazzei injector was utilized for air injection and water application (Fig. 2). Irrigation commenced when soil moisture reached the refill point. Irrigation input during the crop period for the oxygation and control treatments was 252.4 and 240.5 mm per hectare respectively (Fig. 3). Rain contribution during the same period was 4250 mm per hectare (Fig. 1). Therefore, the proportion of irrigation to total crop water input was only 5.5%. All irrigation events were scheduled for supplementary and strategic applications to the crop.

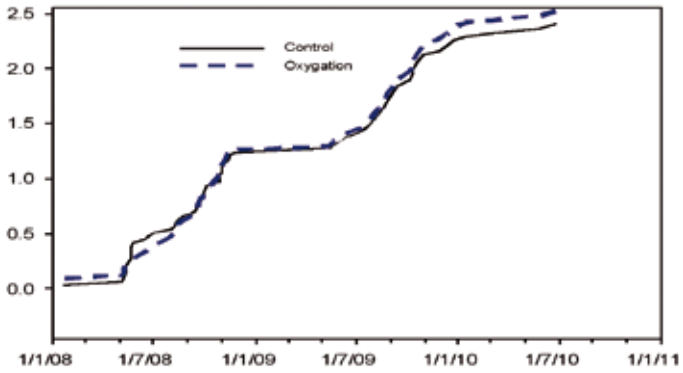

Fig. 3 - Cumulative irrigation input (ML ha^{-1}) over the crop period for oxygation and control treatments.

Soil moisture in the profile

Soil moisture at 40 cm was consistently higher than at 20 cm, irrespective of the treatment (Fig. 4).

Oxygation maintained somewhat less soil moisture compared to the control at both depths. On a number of occasions, the soil moisture content was well above the field capacity (36 mm for 100 mm soil depth) at greater depths, particularly in the control treatment. The results suggested that soil moisture increased with increasing depths (0-60 cm), irrespective of the treatment (Fig. 5). The effect of irrigation treatments on soil moisture was evident, as soil moisture always remained lower with oxygation compared to the control for all the depths in spite of slightly higher irrigation input associated with oxygation, suggesting that water loss from the rhizosphere was greater through transpiration for plants with the oxygation treatment.

Soil oxygen dynamics

Soil oxygen concentration in the oxygated rhizosphere remained higher (7.5 *vs* 4.4 ppm) than the control. The highest oxygen concentrations (10.72 and 7.08 ppm) were noted during irrigation for the oxygation and control groups, respectively. The lowest concentrations for oxygation and control were 5.48 and 3.09 ppm, respectively

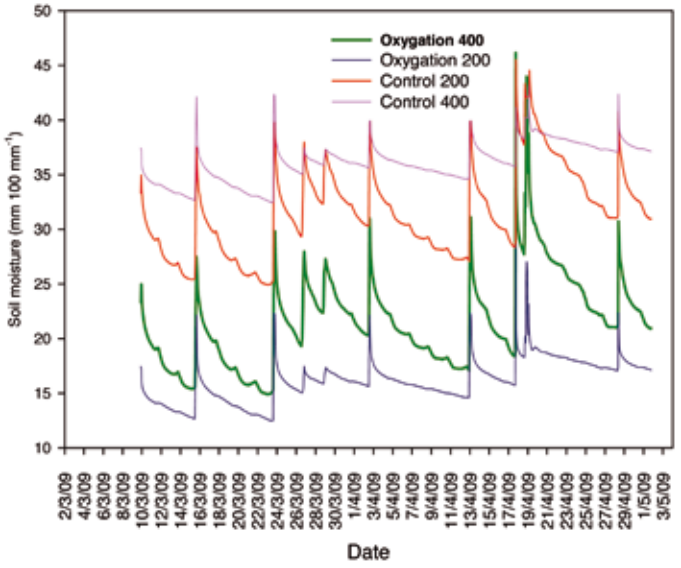

Fig. 4 - Change in soil moisture (mm water 100 mm^{-1} of soil depth) at two different depths (400 and 200 mm) over the period of two months (March-April 2009) in the oxygation and control treatments measured by Red Light Green Light soil moisture sensors.

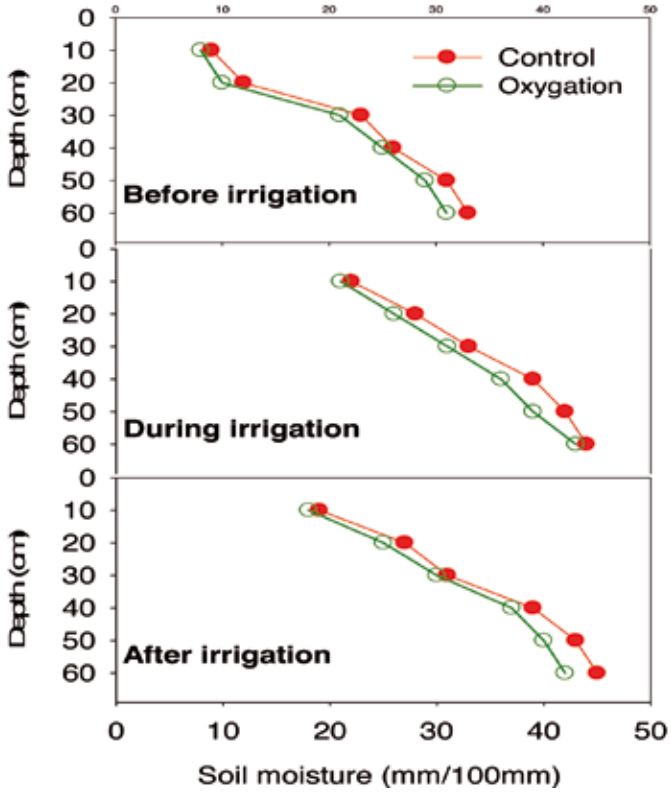

Fig. 5 - Change in soil moisture (mm water 100 mm^{-1} of soil depth) over a period of four days [before (2 days), during (upon completion of 2 hr irrigation) and after (2 days) irrigation] in the oxygation and control irrigation.

(Fig. 6). A higher oxygen concentration in the rhizosphere during oxygation events compared to non-aerated water irrigation was also reported by Chen *et al.* (2010) in cotton and wheat crops in both vertisol and ferrosol under similar climatic conditions.

greater soil resistance in the wetting fronts of cotton under oxygation compared to the control. Such a response was linked with rapid water uptake and transpiration by oxygated plants and, therefore, a drier soil in the wetting front region that contributed to greater soil resistance.

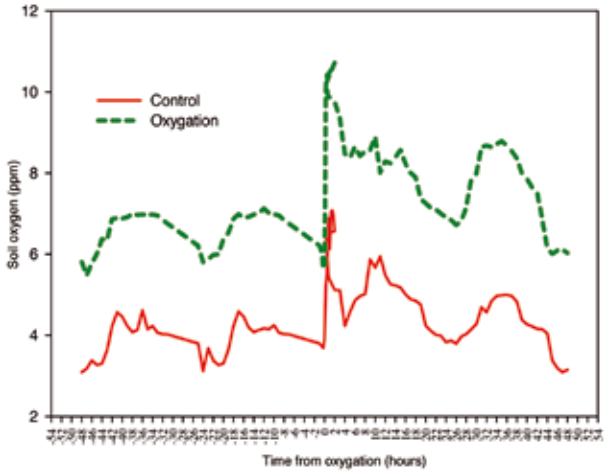

Fig. 6 - Change in soil dissolved oxygen concentration (ppm) over the period of four days [before (2 days), during (upon completion of 2 hr irrigation cycle) and after irrigation (2 days)] in the oxygation and the control treatment measured at the wetting front.

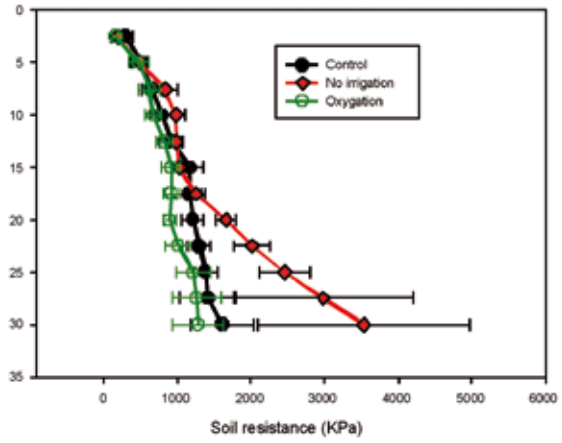

Fig. 7 - Soil compaction measured in the soil at field capacity at the end of the ratoon crop as influenced by soil depth for oxygation (open circle), control (closed circle), and non-irrigated (closed diamond) treatments.

Changes in soil physical properties

Soil compaction. There was less soil compaction in the oxygation treatment compared to the control, and it was higher in the non-irrigated treatment, particularly at depths below the position of emitters (Fig. 5). Soil resistance increased down the soil profile to 37.5 cm depth, and the treatment effect was consistent over this depth. The data suggest that the lower soil resistance down the profile was consistently maintained throughout the profile in the oxygation treatment (Fig. 7) compared to the control and no-irrigation treatments, particularly in the positions below the emitter depths. This observation is in contrast to the report presented by Bhattarai and Midmore (2010 unpublished data) on cotton in vertisol where they showed a

Soil bulk density and air filled porosity. A tendency for lower air filled porosity was recorded in the no-irrigation treatment compared to irrigated oxgation and control treatments. Air-filled porosity at field capacity did not differ significantly between the treatments (Table 1). However, the air field porosity at near saturation was significantly greater in the irrigated control and higher in oxygation compared to the no-irrigation treatment. While no significant difference between the treatments was noted for the soil bulk density, root density was significantly lower (reduced by one half) for the no-irrigation treatment compared to both oxygation and control treatment (Table 1). Non irrigated plants showed shallower root systems, and were easier to pull by hand. Instead of putting down deep rooting, they tended to produce adventitious root in the soil surface. Consistent with these results, Schneider *et al.*

Table 1 - Soil physical and biological properties assessed at the end of the ratoon crop for oxygation, control and no-irrigation treatments

Treatments	Air filled porosity (%)		Bulk density (g/cm^3)	Root density (kg/m^3)	Fluorescence release (µg /g dwt soil/ hr)	*Phytophthora* (% plants)
	Near saturation	Field capacity				
Control	2.6	20.7	1.68	6.32	2.2	4.9
Oxyation	2.3	20.6	1.61	7.50	2.2	3.0
No-irrigation	2.0	18.3	1.61	3.56	1.8	10.5
P value	0.021	0.102	0.243	0.047	0.890	<0.001
LSD (p≤0.05)	0.537	NS	NS	1.811	NS	1.379

Mean separated by LSD.
NS= not significant.

(1992) reported deep penetration of roots and greater root biomass near the drip line and major concentration of root mass at 30-40 cm depth in drip irrigated pineapple on a silty clay soil in Hawaii USA.

Soil respiration

In the ratoon crop, the rate of soil respiration did not differ significantly between the oxygation and control treatments three days after irrigation, however the rate was greater for the irrigated treatments compared to no-irrigation treatment. The diurnal pattern of soil respiration showed a greater soil respiration rate during the day and during the night compared to the early morning and evening (Table 2). In the fast growing pineapple crop, i.e. before the first crop harvest, soil respiration was significantly greater in the oxygation (2.2 g CO_2 m^{-2} hr^{-1}) compared to the control (1.4 g CO_2 m^{-2} hr^{-1}) treatment, an increase of 64%, at 394 days after planting (Chen *et al*., 2010), and following 6 hr of irrigation. Root respiration has been shown to be enhanced by aeration in a number of previous studies on oxygation. These findings are in accord with those of Bhattarai *et al*. (2005) who showed that oxygation increases the amount of oxygen in the irrigation water and ultimately in the root zone, which drives greater root respiration, and therefore ameliorates the temporal hypoxia associated with wetting fronts.

Table 2 - Soil respiration, soil temperature, and soil resistance for different irrigation treatments and diurnal sampling

Treatments	Soil respiration (g CO_2/m^2)	Soil temperature (°C)	Soil resistance (kPa) (2.5-30 cm)
Control	0.82	26.8	1285.2
Oxygation	0.82	26.5	1012.8
No-irrigation	0.37	27.1	2067.5
P value (Aeration)	0.018	0.030	<0.001
LSD (p≤0.05) (Aeration)	0.329	0.423	434.1
Day (1300 hrs)	0.89	29.5	-
Evening (1900 hrs)	0.51	26.2	-
Night (2300 hrs)	0.99	26.1	-
Morning (0500 hrs)	0.57	25.2	-
P value (Diurnal)	0.008	<0.001	
P value (A x D)	0.287	0.726	
LSD (p≤0.05) (Diurnal)	0.327	0.420	-
LSD (A x D)	NS	NS	-

Mean separated by LSD.
NS= not significant.

Soil biological properties and Phytophthora

Low FDA values were noted in the no-irrigation treatment compared to irrigation treatments without significant differences. A marked effect of irrigation treatments was noted on the development of *Phytophthora* symptoms in the field crop (Table 2). The oxygation treatment showed significantly lower infection (3%) compared to the no oxygation SDI treatment (4.9%), whereas the highest *Phytophthora* infestation (10.5%) was recorded in the no-irrigation treatment. In spite of the lower water application rate and reasonably dry soil surface in the no-irrigation plot, development of *Phytophthora* was more severe in this treatment. Exposure of the roots to the soil surface provides poor anchorage to the plant. When the plant was loaded with fruit, the top-heavy weight of the plant resulted in crop lodging and damage to the roots. This may have predisposed the plants to *Phytophthora* contamination particularly when the plot was wet due to rainfall. Severe crop lodging was noted in the non-irrigated treatment in this trial site. A study by Stirling (2004) also suggested that the pineapple crop in QLD in a ferrosol treated with cane trash mulch and under minimum tillage, both of which contribute to maintaining greater soil aeration status, recorded a high FDA level and a positive correlation with greater nematode suppression in the field compared to non-mulched traditional tillage treatments.

Soil chemical properties (nutrients)

Soil organic carbon, Colwell K and Colwell P contents were higher (the latter two not reaching significance at P<0.05) in the no-irrigation treatment compared to oxygation and control treatments when analysed at the end of the crop period. In contrast, soil pH ($CaCl_2$) was significantly lower, and exchangable K was signifcantly higher in the no-irrigation treaments compared to irrigated control or oxygation treatments (Table 3). No significant effects of irrigation treatments were detected for total N, electrical conductivity, and exchangeable calcium and magnesium concentration in the soil.

Table 3 - Macro nutrients, organic carbon, soil pH, conductivity (Cond) and exchangeable calcium (Exc. Ca), exchangeable magnesium (Exc. Mg), exchangeable potassium (Exc. K) in the soil sampled after the ratoon crop in oxygation, control and no-irrigation treatments

Treatments	Organic carbon (%)	N Total (%)	Colwell P (mg/kg)	Colwell K (mg/kg)	Cond (dS/m)	pH ($CaCl_2$)	Exc. Ca (meq/100g)	Exc. Mg (meq/100g)	Exc. K (meq/100g)
Control	0.900	0.06	19.00	61.50	0.04	3.45	0.22	0.06	0.04
Oxygation	0.890	0.07	17.50	56.50	0.05	3.50	0.18	0.05	0.05
No-irrigation	1.210	0.08	45.00	107.00	0.05	3.30	0.31	0.08	0.12
P value	0.064	0.14	0.009	0.086	0.572	0.033	0.547	0.485	0.008
LSD	NS	NS	NS	NS	NS	0.129	NS	NS	0.031

Mean separated by LSD.
NS= not significant.

Plant growth and development

Dry matter partitioning during growth of the main crop

The effect of oxygation was assessed on vegetative and reproductive biomass of the main crop during the early fruit growth stage prior to maturity (392 DAT). Dry weight in the root, leaf, fruits and total above-ground dry biomass increased significantly due to oxygation compared to the control. However, the stem dry weight was not affected by the treatments. The size of the immature fruits (measured as weight of individual fruit) was significantly larger with oxygation compared to the control harvested at the same time (Table 4).

The fruit dry weight was greater by 14% with oxygation compared to the control and, dry biomass was 13% greater in the oxygation compared to the control treatment (Table 4). These results are consistent with yield increases in previous trials on other crops such as tomato, zucchini and cotton representing the C_3 pathway for CO_2 assimilation (Bhattarai *et al*., 2005).

Dry matter partitioning during the growth of the ratoon crop

Dry matter partitioning was carried out for the ratoon crop during the growth phase, at the same time as the diurnal measurements of gas exchange (713 DAT). Above-ground and total dry matter biomass increased with oxygation compared to the control, but without significant differences. However, the increase in leaf dry weight associated with oxygation, compared to the control, was significant (Table 5). The leaf weight with oxygation at 22.9 t/ha was 15% greater than that for the control. This result in the ratoon crop was similar to that in the main pineapple crop, where leaf weight increased by 14%.

The total biomass was 35.4 t/ha with oxygation, which was 7% more than in the irrigated control (31.2 t/ha). This result is also consistent with, but somewhat less than, the result in the main pineapple crop, where the biomass increase was 14%. The oxygation treatment improved root biomass in the main crop (79%) and much less so in the ratoon crop compared to the non-oxygated control. The result in the main crop was consistent with the hypothesis that oxygation improves oxygen availability in the rhizosphere, which positively influences the availability and uptake of water and nutrients favorable for increased root growth and enhanced soil microbial functions (Goorahoo *et al.,* 2002). The lower soil compaction in oxygation treatment plots could also have favoured root growth.

Crop physiological performance

Leaf chlorophyll

Leaf chlorophyll content was estimated using a SPAD meter. A standard calibration for SPAD was also made with acetone chlorophyll extraction method (Arnon, 1954) and a close agreement was achieved between these two methods (Fig. 8) as reflected by the coefficient of determination (R^2=0.807). The chlorophyll content in the D leaf of the ratoon crop was recorded as higher with oxygation compared to the control and no-irrigation treatments. The increase in leaf chlorophyll content was to the order of 11-17% with oxygation compared to that of the control and no-irrigation treatments (Table 6).

Table 4 - Effect of oxygation on plant dry weight and its components at the sample harvest of the main crop (392 DAT) from irrigated control and oxygation treatments (no irrigation treatments were not sample harvested in main crop)

Treatments	Stem (g/m^2)	Root (g/m^2)	Leaf (g/m^2)	AGDB [z] (g/m^2)	Fruit (g/fruit)	Total (g/m^2)	Root/Shoot
Control	585.9	582.3	1760.0	2345.9	833	2928.2	0.248
Oxygation	671.8	1056.1	2232.0	2903.8	1002	3959.9	0.363
P value	0.633	0.004	0.025	0.001	0.016	0.004	0.071
LSD (p≤0.05)	NS	343.5	555.8	323.7	124.7	367.5	0.109

[z] Above-ground dry weight.
Mean separated by LSD.
NS= not significant.

Table 5 - Effect of oxygation on dry plant weight and its components at harvest of the ratoon crop (713 DAT)

Treatments	Stem (g/m^2)	Root (g/m^2)	Leaf (g/m^2)	Crown (g/m^2)	Fruit (g/m^2)	AGDB (g/m^2)	Total (g/m^2)	Root/Shoot
Control	549	528	1942	9.9	85	2587	3115	0.204
Oxygation	598	533	2289	14.7	105	3007	3541	0.177
No-irrigation	623	409	2136	0.0	0.0	2760	3169	0.148
P value	0.76	0.32	0.08	0.62	0.53	0.20	0.22	0.34
LSD (p≤0.05)	NS	NS	150	NS	NS	NS	NS	NS

Mean separated by LSD.
NS= not significant.

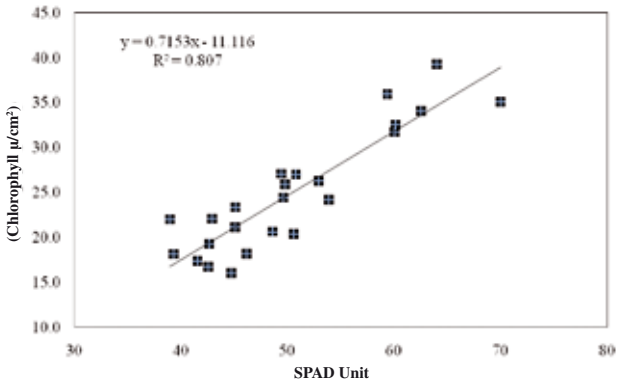

Fig. 8 - Relationship between the SPAD unit and leaf chlorophyll concentration by acetone extraction method.

'D' Leaf characters

A significant increase in plant height was recorded in oxygation and control treatments compared to no-irrigation plants. Although in the first crop there was no effect of oxygation on the number of leaves per plant, nor on 'D' leaf area and the specific leaf area (SLA) of the 'D'leaf (nor on plant height, data not presented), a significant increase in 'D' leaf area due to SDI with or without oxygation compared to the non-irrigated control was evident in the ratoon crop (Table 6). A larger 'D' leaf area has been linked with higher yield of pineapple fruits in a number of previous studies (e.g., Fournier *et al*., 2007).

Canopy light interception

Light interception by the canopy increased significantly with oxygation compared to the control and no-irrigation treatments (Table 6). Light interception by the canopy was highest (92%) in the oxygation treatment and increased by 5% and 7% compared to the no-irrigation and control treatment respectively (Table 6).

Leaf photosynthesis

There was a distinct diurnal pattern for leaf gas exchange. No gas exchange activity was recorded during the daytime, while the carbon dioxide exchange rate ranged between 2.4-3.5 µmol m^2 s^{-1} over the early morning, evening and night (Table 7). A higher CO_2 exchange rate was noted in the oxygation treatment compared to the control

Table 6 - Pineapple leaf characteristics of the ratoon crop as affected by irrigation treatments when harvested at the fruit developing stage

Treatments	Plant height (cm)	Leaf (No./plant)	'D'- Leaf area (cm^2)	'D'- Leaf weight (g)	SLA[z] (cm^2/g)	Chlorophyll (SPAD units)	LI [y] (%)
Control	98.0	9.6	263.23	5.81	46.8	44	87
Oxygation	102.0	8.9	280.45	6.15	48.2	49	92
No-irrigation	93.3	7.9	215.31	5.03	45.4	42	83
P value	0.06	0.82	0.01	0.31	0.63	0.08	0.09
LSD (p≤0.05)	5.8	NS	33.11	NS	NS	5.2	5.6

Mean separated by LSD.
NS= not significant.
[z] SLA = Specific leaf area.
[y] LI = Light interception by the canopy.

Table 7 - Diurnal variation for leaf CO_2 exchange rate, stomatal conductance, transpiration rate, and leaf temperature for different treatments

Treatments	Leaf CO_2 exchange rate (µmol/m^2/s)	Stomatal conductance (mmol/m^2/s)	Transpiration rate (mmol/m^2/s)	Leaf temperature (°C)
Control	2.038	0.312	2.75	30.7
Oxygation	2.198	0.376	2.80	30.6
No-irrigation	1.850	0.150	2.71	31.1
P value (Aeration)	0.39	0.428	0.062	0.033
LSD (p≤0.05)	NS	NS	0.09	0.396
Day (1300 hrs)	-0.14	0.018	1.27	38.5
Evening (1900 hrs)	3.53	0.196	3.21	27.7
Night (2300 hrs)	2.39	0.353	3.69	27.6
Morning (0500 hrs)	2.93	1.324	5.30	27.5
P value (Diurnal)	<0.001	<0.001	<0.001	<0.001
LSD (p≤0.05) (Diurnal)	0.585	0.463	1.034	0.451
P value (A x D)	0.791	0.135	0.082	<0.001
LSD (p≤0.05) (A x D)	NS	NS	NS	0.966

Mean separated by LSD.
NS= not significant.
A x D = Interactions between aeration and diurnal measurement for the given parameters.

and no-irrigation. The diurnal pattern of leaf gas exchange in photosynthesis in pineapple is characteristic of the Crassulacean acid metabolism (CAM), in which carbon dioxide is temporarily fixed during the night and in conditions of very low light intensity as in other succulent plants (Cushman, 2001).

Pineapple crops are able to cope with seasonal variations in weather such as rainfall, dry atmosphere and drought, all of which reduce productivity, due to their ability to assimilate CO_2 via the CAM pathway (San-José *et al.*, 2007). During the day stomata are closed and leaf surface transpiration is at its lowest (Zhu *et al.*, 1999). Due to this unique CAM physiology, pineapple exhibits high WUE, several times higher than C_3 and C_4 plants (Cushman, 2001). Our leaf gas exchange data were collected as point source data, from small portions of the leaf and were instantaneous measurements, hence raising questions as to whether the observations made in a single leaf in instantaneous time frames can reflect the response of the whole plant over an integrated time scale.

Leaf transpiration, stomatal conductance and temperature

Leaf transpiration was low during the day and higher in early morning, evening and night (Fig. 9), and was lower for control and no-irrigation treatments compared to oxygation (Table 7). The stomatal conductance was somewhat higher for the oxygation compared to the control and no-irrigation treatments; however, the difference in stomatal conductance between the treatments was not statistically significant (Fig. 9).

In contrast, the leaf temperature measured during gas exchange decreased significantly with irrigation compared to the no-irrigation treatment (Table 7). Higher leaf transpiration rate is associated with evaporative cooling of the leaf surface that reduces leaf temperature in relation to the ambient temperature of the leaf environment.

A significant interaction between irrigation method and diurnal time scale was due to significantly higher predawn leaf temperature in no-irrigation treatment compared to aerated SDI and SDI control (Table 7). This is due to low transpiration, and slow evaporative cooling of leaf in this treatment compared to other irrigated treatments in the experiment (Table 7).

Fruit yield

The harvest from sub-sample areas at maturity was comprised of all fruits irrespective of their size and marketability. The total pineapple fruit yield (consisting of main crop and ratoon) was significantly greater with oxygation (133.7 t/ha) compared to that of the irrigation control (106.4 t/ha), and least in no-irrigation treatment (90.4 t/ha). The total yield increase due to oxygation was 48% compared to no-irrigation, and 26% compared to the control (Table 8). The harvest yield was greater in the main crop compared to the ratoon crop. The total harvest of the ratoon crop was only 51% that of the main crop, averaged over all three treatments. However, oxygation still maintained a higher yield compared to the control and no irrigation in the ratoon crop.

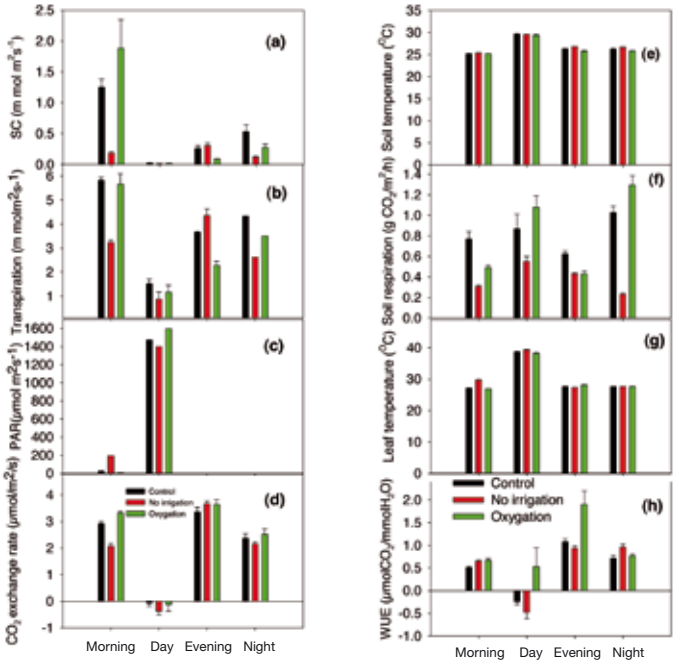

Fig. 9 - Leaf stomatal conductance (a), transpiration rate (b), photosynthetically active radiation (c), CO_2 exchange rate (d), soil temperature (e), soil respiration (f), leaf temperature (g) and instantaneous water use efficiency (h) in oxygation, control and no-irrigation treatment over the time period of 24 hr (bar shows mean, line shows standard error of the means) in a ratoon pineapple crop.

Table 8 - Pineapple fruit yield from the sample area (harvested yield) and industry marketable harvest (industry yield) for the main and ratoon crops

Treatments	Harvested yield (t/ha) [z]			Industry yield (t/ha) [y]		
	Main crop	Ratoon	Total	Main crop	Ratoon	Total
Control	68.20	38.17	106.37	50.92	18.25	69.17
Oxygation	79.60	54.11	133.71	53.08	20.18	73.26
No-irrigation	71.30	19.07	90.37	49.50	16.42	65.92
P value	0.005	0.001	0.032	0.295	0.051	0.076
LSD (p≤0.05)	6.43	10.76	12.36	NS	3.17	7.39

Mean separated by LSD.
NS= not significant.
[z] Harvested yield is all fruits harvested from the sample area.
[y] Industry yield refers to only marketable yield harvested on whole plot basis by the industry picking process.

Total industry fruit yield was highest in the oxygation treatment (73.3 t/ha), followed by control (69.2 t/ha) and no-irrigation (65.9 t/ha). The marketable fruit yield in the industry harvest was greater by 11% due to oxygation compared to the no-irrigation treatment, and 6% compared to the control treatment (Table 8). The industry yield as a proportion of the sampled yield was also greater in the main crop compared to the ratoon crop. The total industry harvest in the ratoon crop was only 36% that of the main crop, averaged over all three treatments. The sample plot yields were considerably higher than the commercially harvested yields due to the fact that commercial yield only considered fruit >1.5 kg; the sample plot yields included fruits which were smaller but mature. The benefits of oxygation for pineapple yields are in agreement with data from oxygation field trials on a vertisol, where lint yield of cotton increased consistently over a number of years and the benefit averaged >10% per annum (Bhattarai and Midmore, 2009).

Fruit quality

The individual fruit weight increased significantly due to oxygation, particularly for the main crop, compared to the control and no-irrigation treatment. The fruits in the oxygation treatment were 230 g and 228 g larger than the control and no-irrigation treatments respectively in the main season crop. In the ratoon crop, the effect of treatments on mean fruit size was not as notable, and the mean fruit size in the no-irrigation treatment had improved considerably. Greater annual rainfall (~1900 mm) that was more evenly distributed compared to the previous year (Fig. 1) minimized crop water stress, and imparted a positive effect on the fruit size and quality in the no-irrigation treatment in the ratoon crop. Other parameters of the fruit size such as fruit height and width were also significantly greater with oxygation compared to the control in the main crop. Such increase in fruit size due to oxygation has also been reported for other crops such as tomato (Bhattarai *et al.,* 2006).

The total soluble solid content measured as °brix and dry matter content remained quite consistent across seasons and treatments. The brix readings were much higher than the minimum brix standard set for Golden Circle (12° brix) and fresh market consumption.

A number of other fruit quality parameters such as fruit translucency, flesh and skin color, flavor and fruit shape were also measured at harvest. Fruit translucency at harvest in the main crop was lower with oxygation compared to that of the control treatment (Table 9), whereas in the ratoon crop the effect of oxygation was significant in lowering the translucency. Low translucency in pineapple at harvest is considered an indicator of better quality fruit. Fruit quality measured by ranking of flesh colour was better under the oxygation: the score for flesh colour ranking was 11% higher (3.29) under oxygation than under the control (2.95). Fruit quality measured by ranking of skin colour was also better in the oxygation treatment. The score for skin colour was 5% higher with oxygation than in the control. Flavor quality of pineapple was also improved with oxygation. The flavor quality score for the sample from the oxygation treatment was 12% higher than the control sample. Although a positive effect of oxygation was recorded on these quality parameters, the differences were not statistically significant in either crop, except for flavor in the main crop and translucency in the ratoon (Table 10).

Water use efficiency

Season-long water use efficiency

For the total harvested yield component, the irrigation water use efficiency (IWUE), which includes only the irrigation component as the water input, increased by 20% due to oxygation (52.98 t/ML) compared to the control (44.23 t/ML). The gross water use efficiency (GWUE), which includes both irrigation and rainfall inputs, increased by 39% due to oxygation (2.97 t/ML), and by

Table 9 - Fruit characteristics and quality parameters of pineapple as affected by irrigation treatments in the main crop

Treatments	Fruit weight (g/fruit)	Fruit height (cm)	Fruit width (cm)	Brix (º)	Density (g/cm^3)	Dry matter (%)	Translucency (1-5) [z]	Flavor (1-3) [y]	Flesh colour (1-5) [x]	Skin colour (1-5) [w]
Control	832.0	12.71	10.32	16.41	0.89	17.51	1.28	2.45	2.95	2.93
Oxygation	1061.8	13.77	10.85	16.55	0.91	17.76	1.10	2.75	3.29	3.07
No-irrigation	834.0	14.50	10.63	15.83	0.97	17.57	2.17	2.83	3.67	3.50
P value	0.045	0.014	0.084	0.719	0.185	0.547	0.11	0.005	0.197	0.564
LSD (p≤0.05)	209.5	0.748	NS	NS	NS	NS	NS	0.167	NS	NS

Mean separated by LSD.

NS= not significant.

[z] Translucency rating: 1 = 0% translucency, 2 = 25% translucency, 3 = 50% translucency, 4 = 75% translucency, 5 = 100% translucency.

[y] Flavor rating: 1 = No flavor, 2 = little flavor, 3 = good flavor.

[x] Flesh colour rating: 1 = 100% white, 2 = 25% yellow, 3 = 50% yellow, 4 = 75% yellow, 5 = 100% yellow.

[w] Skin colour rating: 1 = 100% green, 2 = 25% yellow, 3 = 50% yellow, 4 = 75% yellow, 5 = 100% yellow.

Table 10 - Fruit characteristics and quality parameters of pineapple as affected by irrigation treatments in the ratoon crop

Treatments	Fruit weight (g/fruit)	Fruit height (cm)	Fruit width (cm)	Brix (º)	Density (g/cm^3)	Dry matter (%)	Translucency (1-5) [z]	Flavor (1-3) [y]	Flesh colour (1-5) [x]	Skin colour (1-5) [w]
Control	793.0	12.40	10.17	16.46	0.90	16.37	1.30	2.41	2.74	2.76
Oxygation	961.0	13.43	10.62	13.80	0.92	16.61	0.92	2.29	2.74	3.22
No-irrigation	988.0	14.68	10.70	15.90	0.97	16.81	2.40	2.80	3.80	3.60
P value	0.061	0.007	0.138	0.09	0.003	0.674	0.003	0.117	0.077	0.473
LSD (p≤0.05)	203.0	1.16	NS	NS	0.03	NS	0.638	NS	NS	NS

Mean separated by LSD.
NS= not significant.
[z] Translucency rating: 1 = 0% translucency, 2 = 25% translucency, 3 = 50% translucency, 4 = 75% translucency, 5 = 100% translucency.
[y] Flavor rating: 1 = No flavor, 2 = little flavor, 3 = good flavor.
[x] Flesh colour rating: 1 = 100% white, 2 = 25% yellow, 3 = 50% yellow, 4 = 75% yellow, 5 = 100% yellow.
[w] Skin colour rating: 1 = 100% green, 2 = 25% yellow, 3 = 50% yellow, 4 = 75% yellow, 5 = 100% yellow.

9% due to the control (2.37 t/ML) compared to the no-irrigation treatment (2.20 t/ML) (Table 11).

For the marketable yield component (i.e. the industry harvest), IWUE increased only marginally due to oxygation, while GWUE increased by 6 % due to oxygation (1.63 t/ML), and by 5% due to the control (1.54 t/ML) compared to the no-irrigation treatment (1.55 t/ML) (Table 11).

Table 11 - Water use efficiency (irrigation water use efficiency and total water use efficiency) of the harvested sample yield and industry yield in different irrigation treatments for the total yield averaged over the main and ratoon crop

Treatments	WUE harvested yield (tonnes/ML)		WUE industry yield (tonnes/ML)	
	IWUE [z]	GWUE [y]	GWUE	GWUE
Control	44.23	2.37	28.76	1.54
Oxygation	52.98	2.97	29.02	1.63
No-irrigation	NA	2.13	NA	1.55
Mean	48.60	2.49	28.89	1.57

[z] IWUE= Irrigation water use efficiency presents tonnes of total harvested fruits per mega liter of applied irrigation.
[y] GWUE= Gross water use efficiency presents tonnes of total harvested fruits per mega liter of applied irrigation + rain contribution in the crop for the entire crop duration. The WUE has been presented for harvested yield (total harvest from the sample area), and industry yield harvested by the industry harvesting crew by the machine (represent total marketable fruits).

These observations are consistent with, but much smaller than, the findings of Bhattarai *et al*. (2005) where greater WUE due to oxygation using SDI tomato was reported, and for cotton and vegetable soybean where season-long WUE for fruit and biomass yield and instantaneous leaf transpiration rate were greater with oxygation (Bhattarai and Midmare, 2009).

Cost benefit analysis/decision support

The additional cost for installing an oxygation unit in an already established sub-surface drip irrigation system involves the purchase of a Mazzei air injector model MI 1583 (AU$ 365), plus fittings and pressure gauges for an existing 3" irrigation pipe (AU$ 135), totaling AU$ 500/ha. The installation cost per unit area can decrease with an increase in the size of the air injector. The estimated yield increment of 7.5 ton/ha/crop with oxygation over the average industry yield of 65.9 ton/ha without irrigation brings an additional return of AU$ 3750/ha in the first crop at a sale value of AU$ 500/ton of fruits for the investment of AU$ 500 for oxygation.

For a new SDI installation, however, the cost with oxygation for pineapple is AU$ 6000. Hence, the repayment period for the investment to oxygated SDI is two crop cycles (six years). SDI infrastructure lasts 15 years, covering five cycles of the crop (three years/crop cycle) with potential additional returns of $18,750/ha over the 15-year period. These comparative estimates have been based on a crop with no-irrigation, particularly in high rainfall years (4500 mm over three years). Crop performance under drier years without irrigation is expected to be much less and under such circumstances SDI offers greater opportunity to deliver strategic irrigation. We conclude that oxygation can improve both yield and quality of ratoon pineapple for an industry scale of operation.

4. Conclusions

The total and marketable fruit yield increased with oxygation and the irrigation control compared to no-irrigation. Aerated water increased the marketable fruit yield (73.25 t/ha) by 11% whereas control treatment increased yield (69.2 t/ha) by 6% compared to no-irrigation (65.9 t/ha). Total yield (both marketable and unmarketable) was greater, significantly so, due to oxygation (133.7 t/ha), compared to the control (106.4 t/ha), and no-irrigation (90.4 t/ha). Yield gain with oxygation was attributed to the larger area and weight per leaf, greater plant height, higher specific leaf area, chlorophyll content and light interception by the canopy compared to the control and no-irrigation. Greater CO_2 exchange rates and instantaneous water use efficiency were recorded for the oxygation compared to

the control and no-irrigation treatments. Carbon dioxide exchange was not measurable during the day, only in the early morning, evening and night.

Aerated irrigation water also reduced *Phytophthora* infestation in the field from 11% in the non-irrigated control to 3%, whereas 5% infestation was noted for control drip irrigation. Hence, the use of aerated drip irrigation demonstrated multiple benefits for yield, quality and *Phytophthora* disease management. The trial seasons were rather wetter than average years, and the in crop total rainfall was 4250 mm (42.5 ML), requiring only small amounts of irrigation (2.405 and 2.524 ML for control and oxygation respectively). Supplementary and strategic irrigation contributed only 5.5% to total crop water input. Nevertheless, this strategic use of irrigation and oxygation led to marked benefits for the pineapple crop yield and quality.

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