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Final Report to APTRC

Improving yields and yield stability in the Australian processing tomato industry

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Executive summary

The Australian processing tomato industry is concentrated in southern NSW and northern Victoria on clay soils irrigated by subsurface drip. Average yields are 80 t/ha (ABS, 2018), but the industry has set a yield target of 200 t/ha so it can remain profitable in the face of rising water prices. Overcoming soil constraints has been identified as a key area for improvement to meet this target.

The goal of this investigatory study was to gain a better understanding of the key factors currently limiting yields of processing tomatoes in the Australian industry. To do this, plant and soil parameters were measured in nine commercial tomato crops on two main soil types (red loams and grey clays) in the central Murray valley during the 2019-20 irrigation season.

Four main factors affected yields at the nine monitor sites: harvest losses; disease; water management and soil type. The perception by the industry that soil constraints are a key limiting factor to achieving higher yields, or the cause of progressive yield decline under continuous tomato production on drip tape, was not generally supported by the observations made in the course of this study.

A key determinant of yield was found to be the amount of time that soils were either waterlogged or water stressed in January and February. Soil type was the primary determinant, with evidence of less upward and lateral movement of water and fertiliser from the drip line in the red loams compared to the grey clays.

The following areas of work were recommended for the red loam soils:
1) better matching of irrigation systems to soil hydraulic properties;
2) soil water and nutrient monitoring to improve irrigation and fertiliser efficiency;
3) trials to find a more profitable rotation and options to minimise cultivation so that soil carbon levels can be increased to create water stable soil aggregates.

Introduction

The Australian processing tomato industry is concentrated in southern NSW and northern Victoria on clay soils irrigated by subsurface drip. Average yields are 80 t/ha (ABS, 2018), but the industry has set a target of 200 t/ha so it can remain profitable in the face of rising costs (e.g. water) and increasing competition from imported product. The industry has identified soil constraints as a key area for improvement to meet this target. This is based on the perception within the industry that an observed progressive drop in yields with each successive year of continuous production is due to soil structural decline under drip irrigation. Research has implicated low pH, high salinity, migration of clays, and coalescence of continually wet soil as issues affecting soil structure and, potentially, water and oxygen supply to plants (Barber *et al.*, 2001; Lanyon and Kelly, 2010; Brown, 2016). Disease has also been implicated and linked to low pH (Ajith, 2019) and waterlogging (Wang, 2020); with bacterial diversity negatively correlated with pH, and fungal diversity with water content, cation exchange capacity, calcium and potassium concentration (Quach, 2017).

Efforts to improve soil structure with liquid gypsum (Yong *et al.*, 2015) and to mitigate waterlogging with oxygation through drip lines have had no significant effect on yields (Brown, 2016). Deep ripping has also been tried by growers, who attribute a return to first year yields in following crops to deconsolidation of hard, coalesced sub-soil (M. Wright, *pers. comm.*). However, deep ripping under tomatoes at Carnarvon had no effect on yields (Muller, 1993). Additionally, the high yield (12 t/ha) in 2018 of a wheat crop which followed four years of tomatoes (J. Gelch, *pers. comm.*) casts doubt on the assumption that any progressive yield decline in tomatoes is due to soil structure.

While pH, disease and soil structure may contribute to low yields and progressive yield decline, it has not been conclusively shown that they are primary causal factors. Furthermore, the range of possible, unexamined factors that could be limiting tomato yields is considerable. A better understanding of the key yield limiting factors is needed if ways of lifting yields are to be found.

Within genetically determined limits, three factors determine the physiological potential yield of any given crop: solar radiation, temperature and water (Beecher *et al.*, 1995; Fischer *et al.*, 2014). Whilst variations in temperature and radiation may account for much of the variation in fruit yields between seasons (Scholberg *et al.*, 2000), soil water will be the key variable that determines within-season yield potential given the industry occurs within only one climatic zone (i.e. the central Murray valley).

There is a linear relationship between transpiration and biomass accumulation (Bierhuizen and Slatyer, 1965; Hanks, 1983; Ritchie, 1983; Tanner and Sinclair, 1983; Ben-Gal *et al.*, 2003). As a result, crops which transpire less have smaller canopies than crops which transpire more, so they intercept less radiation and have lower yields (Tan, 1993). Transpiration is reduced when stomates close in response to water deficit (Nicacias, 2009) or waterlogging (Sojka and Stolzy, 1980), and this reduction in transpiration causes canopy temperature to increase relative to ambient air temperature (Tan, 1993; Nicacias, 2009).

Previous studies (Barber *et al.*, 2001; Lanyon and Kelly, 2010; Yong *et al.*, 2015; Brown, 2016; Ajith, 2019; Quach, 2017; Wang, 2020) have assumed that a measured condition known to be deleterious to yield (e.g. low pH, waterlogging, presence of disease organisms) is the cause of the low yield. However, none have related the intensity and duration of the condition being measured during the season with the response of the plant through the season. As a result, they have not successfully been able to determine causation. Fruit yield reflects the sum of accumulated stresses experienced by the crop throughout the season. It is not a direct indicator of crop stress *per se* because of the plasticity of plant responses to stress and the ability of plants to compensate for an earlier stress during later growth. Neither is fruit yield a good indicator of a single stress in field situations where multiple stresses occur together.

Unlike yield, tomato canopy temperature may provide a direct measure of plant response to water stress at the time the stress is imposed (Gupta *et al.*, 2017). Measuring soil water and oxygen status at the same time as canopy temperature makes it possible to determine whether an observed plant stress is associated with a water deficit or excess. If a correlation between canopy temperature and canopy growth and size can be found, and if this is reflected in fruit yield, then this will allow a causal link to be drawn between the observed stress and its effect on yield.

The goal of this investigation is to gain a better understanding of the key factor or factors currently limiting yields of processing tomatoes in the Australian industry. The hypothesis is that yields are limited by soil water, either in shortage or excess. Three questions are posed:

1. Are lower yields associated with smaller canopies?
2. Are smaller canopies associated with warmer canopies?
3. Are canopies warmer because they are water stressed or waterlogged, or because of some other reason, and how are these correlated to yield?

The outcomes of this work will be used to inform future investment to meet the industry's 200 t/ha target. If it can be shown that smaller canopies are associated with lower yields and higher canopy temperatures, and that this is correlated with transient water shortage or waterlogging, then future investigations will be directed towards improving soil structure, irrigation systems and water management. On the other hand, if lower yields occur despite optimal soil water and oxygen, then other factors will need to be investigated.

Methods

Nine commercial tomato crops at eight locations were selected for monitoring during the 2019-20 season. All sites were in the Murray valley (Figure 1) and were selected to provide data from the two major soil types used by the industry: duplex, red loams (chromosols; Isbell & NCST, 2016) and uniform grey clays (vertosols; Isbell & NCST, 2016). Four sites were selected within each soil type group to obtain data from crops which had (1) a range of years in tomato production and (2) different drip emitter rates. At one red loam site (Site BA), two adjacent blocks were monitored: Site BA-7 had nine-year-old drip tape and Site BA-6 had been ripped and new tape laid in October 2019. Where possible, sites were selected which grew a common variety (i.e. H3402). Details for each site are shown in Table 1

Efforts were made to select sites to provide information across a range of variables (emitter rate, history of tomato growing, variety) within each of two soil groups. It was presumed that crop management would be similar across all sites and this was generally the case. However, all red loam sites were managed by Kagome and all bar one of these sites grew UG varieties, whereas all grey clay sites were managed by owner-growers who grew the H3402 variety (Table 1). It would therefore be incorrect to draw any inference from this study about the effect of soil type on yield as it is confounded by both management and variety.

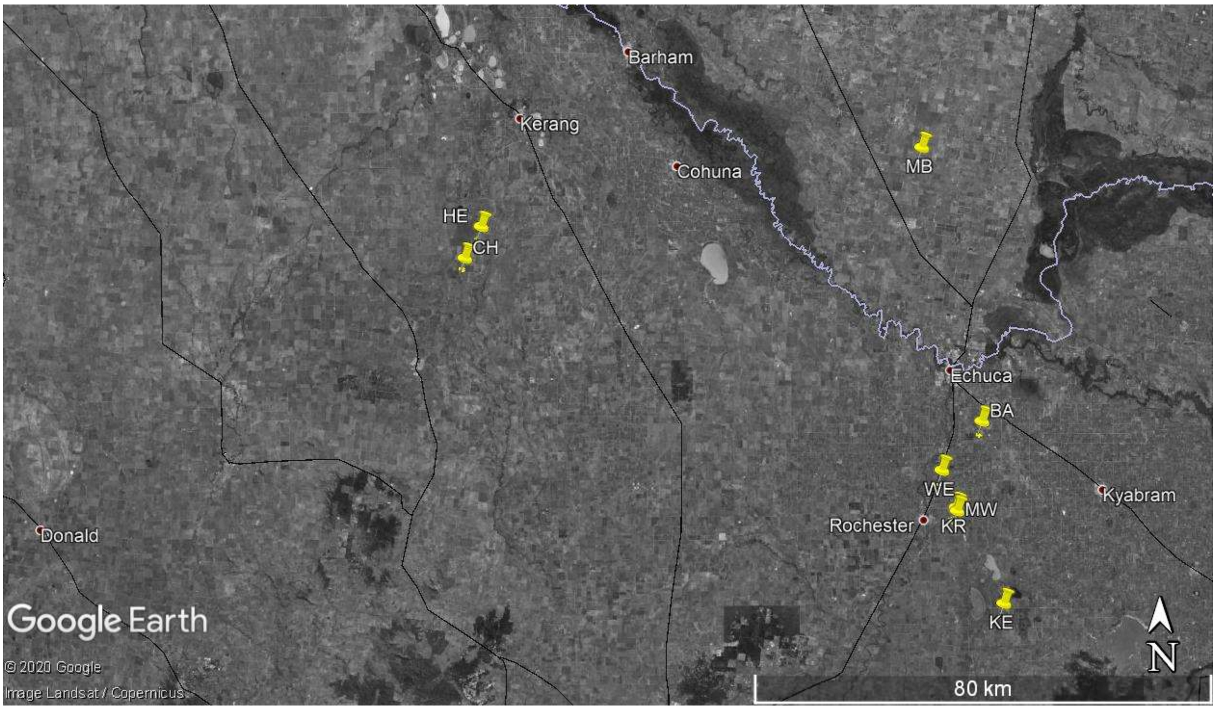

Figure 1. Location of the sites where processing tomato crops were monitored in the 2019-2020 summer cropping season (source: GoogleEarth™).

Table 1. Details of the nine commercial crops monitored during the 2019-20 season

Site	Crop manager	Soil type	Emitter rate *(L/hr)*	Row Space *(m)*	Tape age *(years)*	Preceding crops	Variety Mix
BA-7				1.52	1	Corn in 2018/19 & 2017/18 Tomato in 2016/17	UG19406 UG16112
BA-6			1.05	1.52	9	Corn in 2018/19 & 2017/18 Tomato in 2016/17	UG19406 UG16112
MB	Kagome	Red loam		1.52	9	Faba beans in 2018 Tomato in 2017/18	H3402 H1175
KR			1.6	1.52	2	Corn in 2018/19 & 2017/18 Tomato in 2016/17	UG19406 UG18806
MW				1.52	4	Tomato in 2018/19 Tomato in 2017/18	H3402 H2401
WE			1.05	1.52	8	20 years since last tomato crop	H3402
CH				1.68	5	Fallow since tomato in 2016/17	H3402
KE	Owner	Grey clay	1.6	1.52	3	Chickpea in 2018 Tomato in 2017/18	H3402
HE				1.68	n/a	Tomato in 2018/19. Re-lasered in 2017/18	H3402 H1311

Soil water, canopy temperature and environmental data

Sensors and loggers were installed at each site in late December or early January after the last in-crop cultivation. These sensors measured the following soil and plant parameters:

- Soil water (matric) potential (Ψ_m) using Watermark™ sensors to measure plant soil water availability, and redox potential (E_h) using Paleoterra™ sensors to assess soil oxygen status:
  - at three depths - 10, 20 and 35 cm
  - mid-bed adjacent to an emitter and 50 cm away on the bed shoulder
  - at two locations 10 m apart on the one bed (Figure 2)
- Sensors (EnviroPro ™) to measure soil water content every 10 cm from 10 to 80 cm deep adjacent to the drip line (i.e. mid-bed) at a location 10 m from the paired Ψ_m and E_h sensors and in the same bed. An additional set of Ψ_m sensors were installed next to the EnviroPro sensor at depths of 10, 20, 30 and 40 cm (Figure 2).
- Two sets of infrared (IR) canopy and air temperature sensors were installed at a height of 1.2 m above the canopy. The IR sensors had a 5° field of view and were angled down 20° from the horizontal to see a crop area of approximately 1.8 m^2. They were oriented 90° from each other to look north across the crop at a 45° angle to the direction of the crop row (Figure 3). These sensors and their loggers were prototypes built by the project team. Technical problems meant they did not work all the time at all sites, particularly in the two weeks after their installation. However, enough data was collected to meet project aims.

Figure 2. Photos showing the set-up of the matric potential loggers (blue boxes), redox loggers (white boxes) and canopy temperature sensors (on the pole) at a monitoring site (left); and the arrangement of matric potential sensors (white PVC) next to the capacitance soil water sensor string (green) at the third replicate location in a monitor site (right).

Figure 3. A logger box with two infrared canopy and air temperature sensors attached.

Crop canopy growth during the season was assessed using the paddock median of each site of the normalised difference vegetation index (NDVI) obtained by Landsat 7 and 8 and Sentinel 2 satellite imagery via the IrriSAT app (https://irrisat-cloud.appspot.com/#). Patched point weather data was obtained from SILO (www.longpaddock.qld.gov.au/silo/) for the period from planting to picking at each site. Temperature data from these records was used to calculate the accumulated thermal time since planting (or two true leaves for the direct seeded crops) using a base and maximum temperature of 10°C and 30°C respectively (Scholberg *et al.*, 2000; Shamshiri *et al.*, 2018).

Crop data

The number of plants, the fresh weight of red, green and rotten fruit, and the fresh weight of above ground vine biomass was obtained from three quadrats (2 m length of one plant row) cut at maturity at each site. Subsamples of red fruit and vine were taken to determine Brix and fruit moisture content (determined by drying at 60°C to a constant weight).

Red fruit yields were corrected for moisture content and are reported at a standard moisture content of 94% (OECD, 2008). The proportion of green and rotten fruit were calculated as percentages from the total raw wet weight of red, green and rotten fruit. Harvest index was calculated from red fruit dry weight / (vine dry biomass + red fruit dry weight).

Root/crown samples were collected at harvest for determination of disease but COVID-19 closed Melbourne University's laboratory where plant pathology was to be undertaken in March. Thus, disease data was only obtained from Site KE.

At the conclusion of the season, forms were sent to all cooperators to collect paddock and input data for each of the nine crops monitored. Information on paddock yields, water and fertiliser inputs, and key observations from each cooperator was collected.

Soil data

Soil samples were collected from each monitor site twice: firstly in December 2019 after the final in-crop cultivation (when sensors and loggers were installed) and secondly in May 2020 after harvest. Samples at each site were taken from three locations near to where the soil sensors were installed at four positions within the bed (Figure 4):

- at the surface (0-5 cm) in both the plant line and on the shoulder of the bed (0.5 m from the plant line);
- at the depth of the drip tape both next to the drip tape and 0.5 m away under the shoulder of the bed.

Two samples were taken at each of the four sample positions in the bed:

1. a grab sample for:
   a. analysis of chemical properties on air dried and ground samples for: pH, electrical conductivity (EC), exchangeable cations (Na, K, Ca, Mg and Al), chloride (Cl), nitrate-N, ammonium-N, Colwell-P, sulphur (KCl) and potassium (ammonium acetate).
   b. Particle size analysis on intact samples using the plummet balance method.
2. intact cores (75 mm diameter by 50 mm high) for bulk density, with two replicate samples taken from each location .

Ceramic soil solution vacuum samplers were installed at a depth of 20 cm in the middle of the bed at one location at each site. Samples of the soil solution were collected on the 4th and 12th February for analysis of pH and electrical conductivity (EC).

Measurement of two soil physical properties was also done during the May site visits:

1. soil strength – soil penetration resistance was collected with a Rimik™ cone penetrometer at intervals of 15 mm from the surface to a depth of 450 mm at locations 20 cm apart on three 7.2 m long transects across 5 beds at each site.
2. hydraulic conductivity – infiltration at the depth of the drip tape and in the plant-line was collected at six locations around each monitor site using constant-head well permeameters (Amoozegar, 1989). The permeameters were constructed to fit water depth loggers (TruTrack™) so the recording of infiltration could be automated for the 4-10 hours it took to obtain a reading.

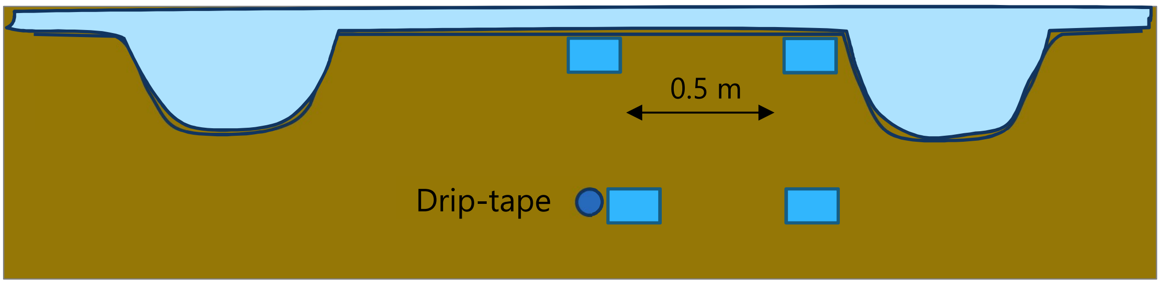

Figure 4. Diagram showing the relative positions of soil sampling locations (light blue squares) and the drip tape (dark blue circle) in the beds.

Statistical analyses

Test for significance were conducted using GraphPad PRISM™ (non-linear regression) and Jamovi™ (correlation analyses).

Results

Weather, crop inputs and yields

Temperatures during the 2019-20 summer cropping season were hotter than average in October and December and cooler in March (Figure 5 left). December was considerably hotter than average, with 7 days over 40°C and a maximum of 46.5°C recorded on the 20th December. The hot temperatures at the start of the season, combined with some very windy days, put pressure on establishing crops, particularly the seeded crops at Boort where gaps had to be filled with transplants. These conditions are reflected in the very much lower than average rainfall in November and December (Figure 5 right), which kept disease pressure low. This changed as the season progressed. At Site KE, rain in January after an irrigation caused the crop to become waterlogged and facilitated the onset of disease. There was a major rain event on the 5th March, with 24 mm falling on the western sites and 50 mm on the eastern sites. Sites KE and MB had been harvested, so were unaffected. However, most of the other sites experienced delays in picking (Table 2) and the rain and cooler, more humid conditions saw disease enter these crops to a greater or lesser degree.

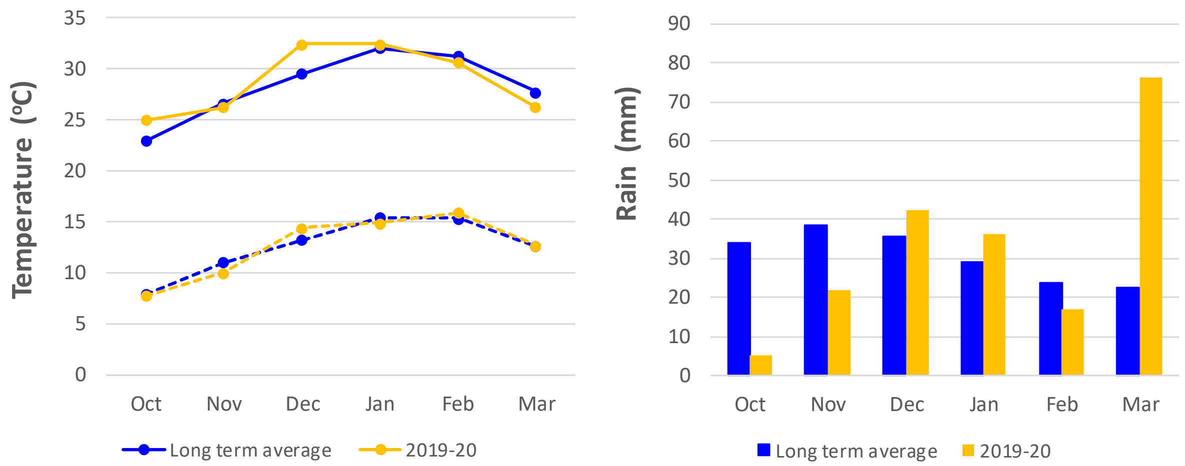

Figure 5. Monthly mean daily maximum (solid line) and minimum (dotted line) temperature (°C) and rainfall (mm) at Echuca airport for the period Oct 2019 to Mar 2020 compared to long term monthly averages from 1991 to 2020 (source: Bureau of Meteorology)

Fruit yields at field moisture contents ranged from 81 to 190 t/ha for the hand-picked quadrats and from 60 to 142 t/ha for the machine picked paddocks (Table 2). There was a strong linear relationship between the quadrat and farmer reported yields (R^2 = 85%), with the quadrat yields being on average 30% higher than the paddock yields. This difference is mainly due to harvest losses with machine picking and better timeliness with hand picking, but there is also likely to be a sample size effect (Davidson and Martin, 1968). However, the strong relationship between the hand and machine picked yields provides confidence in the inferences drawn from the data obtained from these sites.

The range in the quadrat yields was reduced to 103 to 182 t/ha when they were corrected to a standard moisture content of 94% (Table 2). The two highest yields were from crops on grey clays (Sites CH and WE). These crops were clean and grew well all season, but rain

Table 2. Yield, harvest component, crop and input data for the nine commercial process tomato crops that were monitored in 2019-20. The red fruit yield in italics and parentheses is the hand-picked yield at 94% corrected for fruit size for comparative purposes. Maximum values are in bold text and crop data collected from co-operators is in dark blue text in the bottom six rows (s = seeded crop; n/r = not reported).

SITE	BA-6	BA-7	CH	HE	KE	KR	MB	MW	WE
Planting or emergence date	4 Nov	21 Oct	5 Nov (**s**)	8 Nov (**s**)	9 Oct	14 Oct	9 Oct	12 Oct	13 Nov
Hand pick (***HP***) date	20 Mar	20 Mar	23 Mar	23 Mar	26 Feb	10 Mar	18 Feb	10 Mar	16 Apr
Season length (*°Cd/days*)	1597	**1723**	1661	1643	1504	1620	1528	1637	**1713**
Plants per ha at harvest	16,500	16,500	42,750	**79,500**	18,000	16,500	17,500	17,500	14,250
Red fruit yield @94% (*t/ha*)	103	105	**182**	145	123	131 (*116**)	148	137	160
Brix	5.9	**6.4**	4.9	4.2	4.9	6.0	4.9	4.6	4.4
Red fruit dry weight (*g/fruit*)	2.7	2.4	2.6	2.5	2.4	**3.6**	2.7	2.5	2.5
% green + % rotten	**17** + 3	**12** + 3	8 + 2	**13** + 4	4 + 1	**16** + 4	9 + 2	5 + 2	**10** + **17**
Harvest index	0.56	0.61	**0.71**	**0.74**	0.66	0.60	0.64	0.68	0.56
Disease (*1=low; 5=high*)	3	**4**	2	2	**4**	3	2	**5**	3
Weeds (*1=low; 5=high*)	**4**	**4**	1	2	2	3	1	3	1
Machine pick (days after ***HP***)	**27**	**25**	**25**	6	0	11	4	2	n/r
Within crop rain (**R**) (*mm*)	137	152	81	81	118	156	61	156	185
Total water (**R**+Irrig) (*ML/ha*)	7.6	8.1	7.8	8.8	6.2	10.0	8.6	8.2	n/r
Total N-P-S (*kg/ha*)	349-91-5	349-91-5	n/r	313-100-8	319-82-7	333-91-5	375-112-5	333-91-5	n/r
Total K-Ca (*kg/ha*)	58-41	58-41	n/r	0-35	118-0	65-41	0-46	65-41	n/r
Grower reported yield (*t/ha*)	60	75	**142**	n/r	90	85	124	95	n/r

* this is the yield at Site KR corrected to the mean fruit size of the other eight sites. It allows inter-site comparison of yield based on the number of fruiting sites.

and delays in picking at the end of the season affected yields at Site WE. The yield at Site HE was similarly affected, with significant losses in rotten fruit at both sites (Table 2). The two lowest yields were from crops on red loams (Sites BA-6 and BA-7). Yields averaged 122 t/ha and 153 t/ha from red loam and grey clay soils respectively. There was also a difference between the two genetic lines, with average yields from the UG and H lines being 108 t/ha and 149 t/ha respectively. However, these differences should not be taken as indicative of a soil type or variety effect as they are confounded, with all the UG lines being on the red loam soils. Moreover, there were other influences which affected yields. Weeds became a major problem late in the season at Sites BA-6 and BA-7, primarily because of poor crop growth at these sites. Disease had a major impact on yields at Site KE and MW which is attributed to waterlogging at Site KE and to a high disease load at Site MW where tomatoes had been grown the two previous summers.

These yield differences occurred despite little difference in the weather experienced between sites and despite the similarity in water and nitrogen inputs: 8 ML/ha and 330-350 kg N/ha respectively (Table 2). Only 6.2 ML/ha was applied to Site KE, yet this crop was waterlogged. It is inferred from this that poor internal soil drainage may be an issue at this site. 10 ML/ha was applied at Site KR, but the reason for this is not known. The major difference in inputs between the crops was in the amount of potassium and calcium applied. Two sites (HE and MB) had no applications of potassium and one site (KE) had no application of calcium.

Canopy growth and fruit yield

The change in the median NDVI of each block where the monitor sites were located is shown plotted against the accumulated thermal time since planting in Figure 6. An asymmetric growth and decay model of crop foliage (Werker and Jaggard, 1979) was fitted to this data. The curves fitted to the crops at Sites CH, HE and WE were not significantly different ($P = 0.46$), so a common curve was fitted to the data from these sites. All fitted curves had R^2 values greater than 96%. The model gave a good fit to the data from Sites BA-6 and BA-7 but it may not have been the best model for these sites as NDVI rose all season and did not decay during ripening like the other crops. This is attributed to the growth of weeds at these two sites, which would have come to dominate the NDVI image late in the season.

There was a very strong correlation ($R^2 = 89\%$) between canopy size, as measured by NDVI (Lobell *et al.*, 2003; Hornbuckle *et al.*, 2016) between 800 and 1200°Cd after planting, and red fruit yield corrected to 94% moisture (Figure 7). Fruit at Site KR were on average 44% larger than at the other eight sites, so the relationship between fruit number and yield from the other eight sites was used to estimate a yield from the number of fruit. These corrections ensure a better, causative comparison because both canopy size and yield reflect the number of fruiting sites when yield is independent of fruit moisture content and size.

The strong correlation between NDVI and yield gives confidence to infer the following:

- The two highest yielding crops (CH and WE) had the highest rate of canopy growth after planting and maintained their canopies through ripening to harvest. Canopy growth at Site HE was not significantly different to that at Sites CH and WE and the lower yield at both Site HE and Site WE in comparison to Site CH can be attributed to rain in March and losses in rotten fruit (see Table 2) associated with this rain.

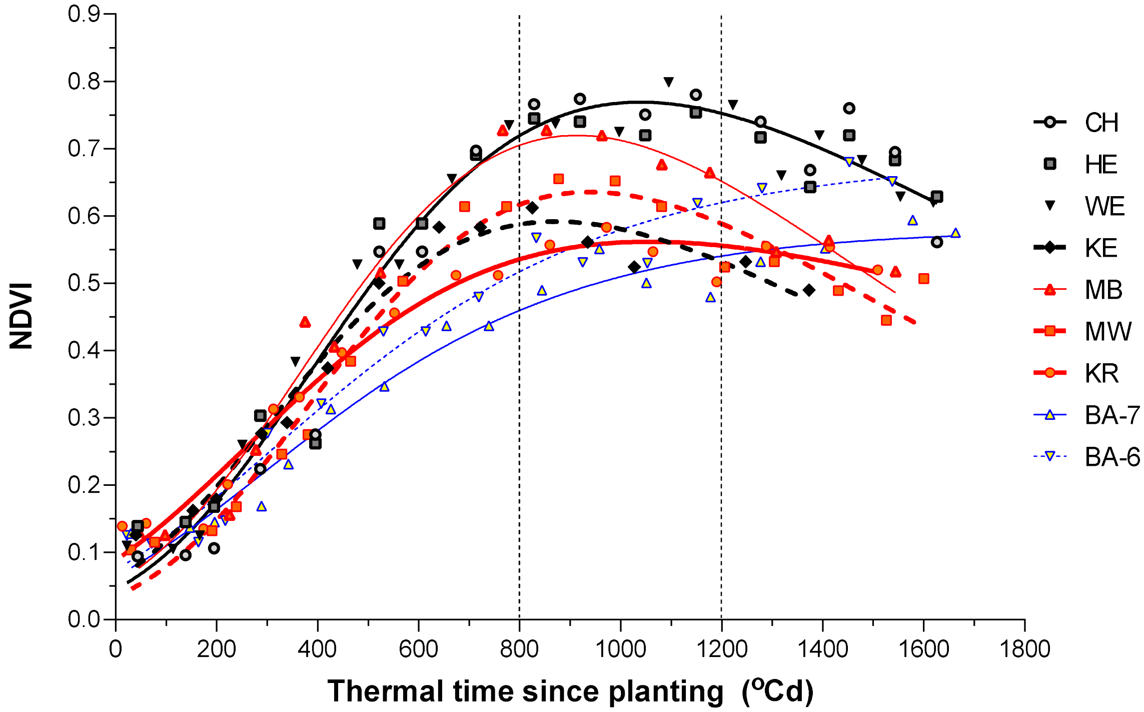

Figure 6. Normalised difference vegetation index (NDVI) from IrriSat (Hornbuckle *et al.*, 2016) plotted against accumulated thermal time since planting/emergence for the crops at the nine monitor sites in 2019-20. A crop foliage model (Werker and Jaggard, 1979) is fitted to the data, with a common curve fitted to the data from Sites CH, HE and WE.

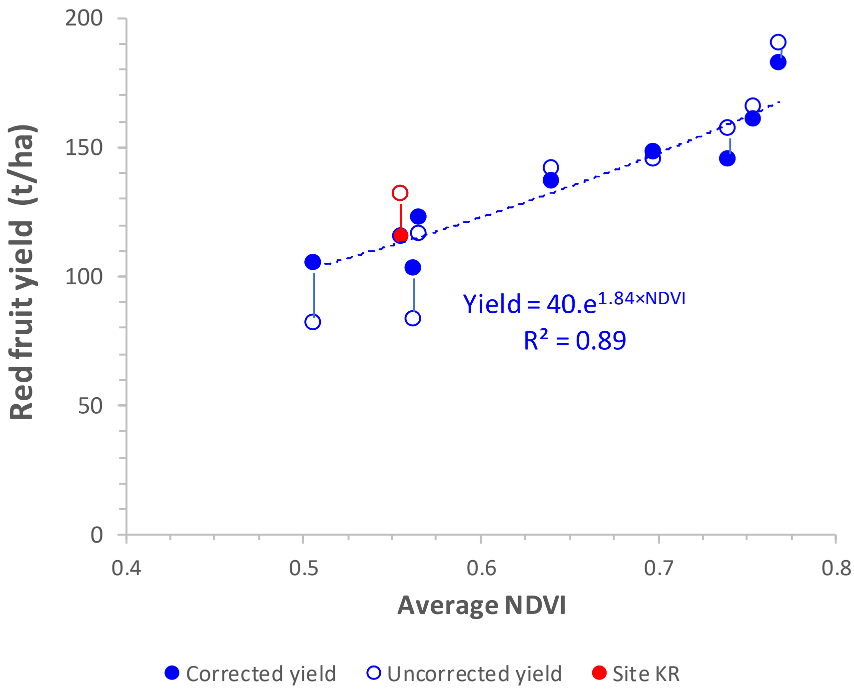

Figure 7. The relationship between quadrat red fruit yield (t/ha) at 94% moisture and the paddock average NDVI measured by IrriSat between 800 and 1200°Cd after planting in 2019-20 for the nine monitor sites. Raw, uncorrected yields (open circles) are shown for comparison. Fruit at Site KR were, on average, 44% larger than at the other eight sites and the adjustment to the yield from that site to account for this is also shown.

- The crop at Site MB initially grew at a similar rate to Sites CH, WE and HE, but something changed after 800°Cd (29th Dec) and the canopy declined rapidly.
- Growth rates at Sites KE and MW fell behind the better crops after 500°Cd (15th Dec), so the canopies at these sites did not reach the same size by 800°Cd as a result.
- Growth rates at Sites KR, BA-6 and BA-7 fell behind that of the better crops after 300°Cd, which was 37 to 41 days after planting at these sites.

Canopy temperature and soil water status

Building and testing the canopy temperature sensors meant they weren't installed until early January, and glitches in programming in some of the loggers meant that it was not until 22nd January that readings were obtained from all sites. Consequently, the canopy temperature (T_c) record did not encompass the vegetative growth period before 800°Cd for any of the nine crops. The temperature record from 22nd January to harvest at each site was continuous.

Canopy temperature has been used to measure water stress in tomatoes (Gupta *et al.*, 2017; Nicacias, 2009). Crop water stress is usually indicated when canopy temperature exceeds ambient air temperature in the hours after solar noon (Jackson *et al.*, 1981), with previous studies in tomatoes using the period between mid-day and 18:00 hours (Amani *et al.*, 1996). Tomato roots in drip irrigated crops occur between 5 and 40 cm depth, with a concentration around the drip-tape (Machado *et al.*, 2003), so matric potential measurements in this zone should also provide a good indication of crop water status (Thompson *et al.*, 2007).

For the period of available record at each site, canopy temperature minus air temperature (T_c-T_a) between 12:00 and 18:00 hours was compared with the matric potential of the soil in the middle of the bed at 15:00 hours. Temperatures were the average of the two sensors and matric potentials were the average of readings from all sensors (10, 20 and 35 cm) in the two replicated sensor arrays located next to the drip line. The results of this comparison showed there was a general trend for canopy temperatures to increase as soils dried, but not all sites dried sufficiently to express this trend and the scatter in the data was too great to provide any confidence in the relationship (Figure 8). The notable feature of this analysis was that (T_c-T_a) indicated plants were stressed (i.e. T_c-T_a > 0) when matric potentials indicated soils were wetter than published threshold limits (Haise and Hagan, 1967; Thompson *et al.*, 2007).

These high canopy temperatures relative to ambient air temperature may be due to poor mixing between air in the canopy and the air overhead. Dense, smooth and short crop canopies such as tomato canopies obstruct air movement so that canopy air temperatures are nearly uncoupled from the air overhead (Alvino and Marino, 2017). The use of air temperature as a reference temperature thus appears problematic for tomatoes. Efforts have been made to develop dry reference sensors for row crops (Jones *et al.*, 2018) but such a reference was not available. However, canopy temperatures from well-watered tomato crops were available to serve as a wet reference (Penman, 1948; Allen *et al.*, 1998). The crops at Sites CH, HE and WE fitted this purpose as they had the same growth curve, they were generally well watered, and they were not affected by disease, waterlogging or weeds. Averaging the daily canopy minus air temperatures from the three reference sites $(T_c\text{-}T_a)_{ref}$ and subtracting this from (T_c-T_a) at the other sites appreciably reduced the scatter in the relationship with matric potential (Figure 9). The soil at Sites MB and BA-7 dried down at the end of the season and, as there was no significant difference between the two data sets (P=0.22), a single straight line was able to be fitted to the data from these two sites (R^2=0.47).

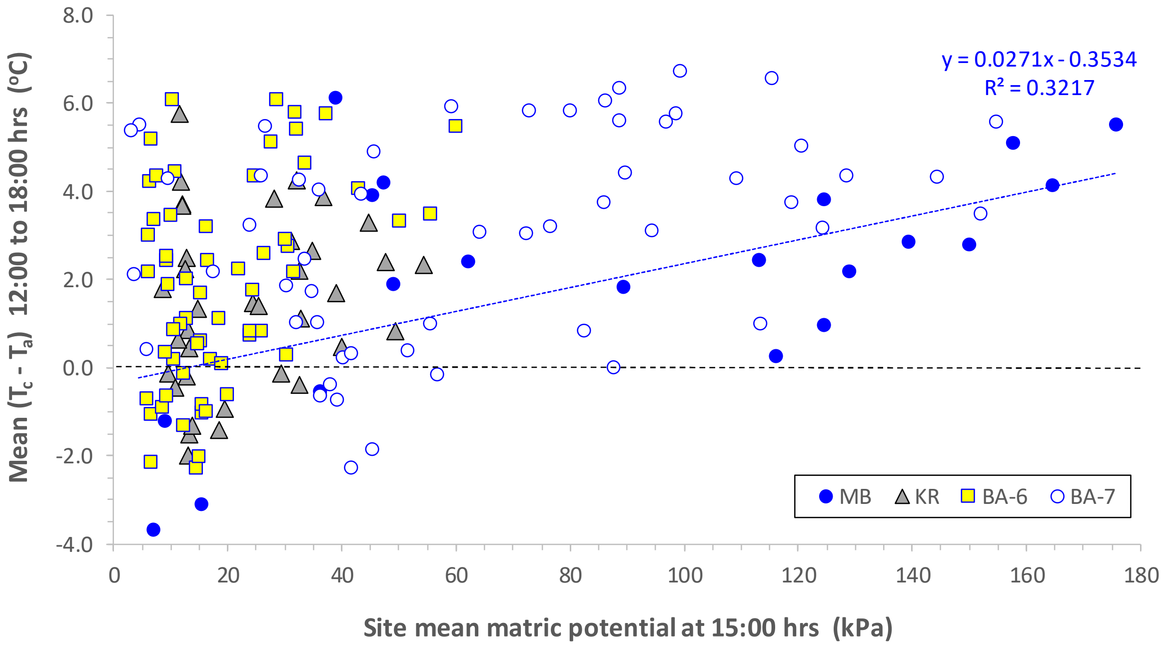

Figure 8. The relationship between daily mean canopy minus air temperature (12:00 to 18:00 hours) and the mean matric potential (0-40 cm) in the centre of the bed at 15:00 hours at Sites MB, KR, BA-6 and BA-7. The least squares line of best fit to the data from Site MB is shown.

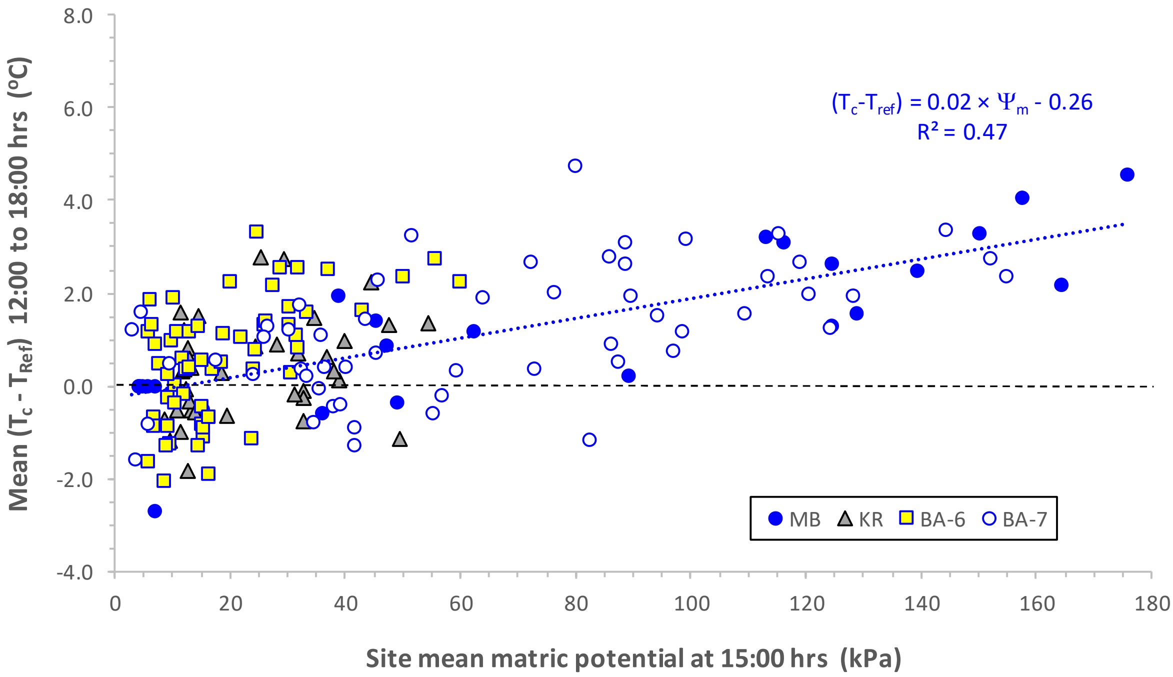

Figure 9. The relationship between average daily canopy minus air temperature (T_c-T_a) less the wet reference temperature ((T_c-T_a)$_{ref}$) from the three reference sites plotted against the mean matric potential (0-40 cm) in the centre of the bed at Sites MB, KR, BA-6 and BA-7. The least squares line of best fit to the combined data from Sites MB and BA-7 is shown.

The relationship between (T_c-T_{ref}) and matric potential at Sites MW and KE was markedly different to that at Sites MB, KR, BA-6 and BA-7 (Figure 10). The soil matric potential in the middle of the bed at Sites MW and KE did not exceed 60 kPa during the measurement period, yet (T_c-T_{ref}) was greater than 4°C at soil matric potentials considerably wetter than the tomato irrigation threshold of 50 kPa (Thompson *et al.*, 2007). Disease is known to increase canopy temperatures in tomatoes (Ryu *et al.*, 2017) and, given both Site MW and KE were affected by disease, this is considered the likely reason for the hotter canopies at these sites.

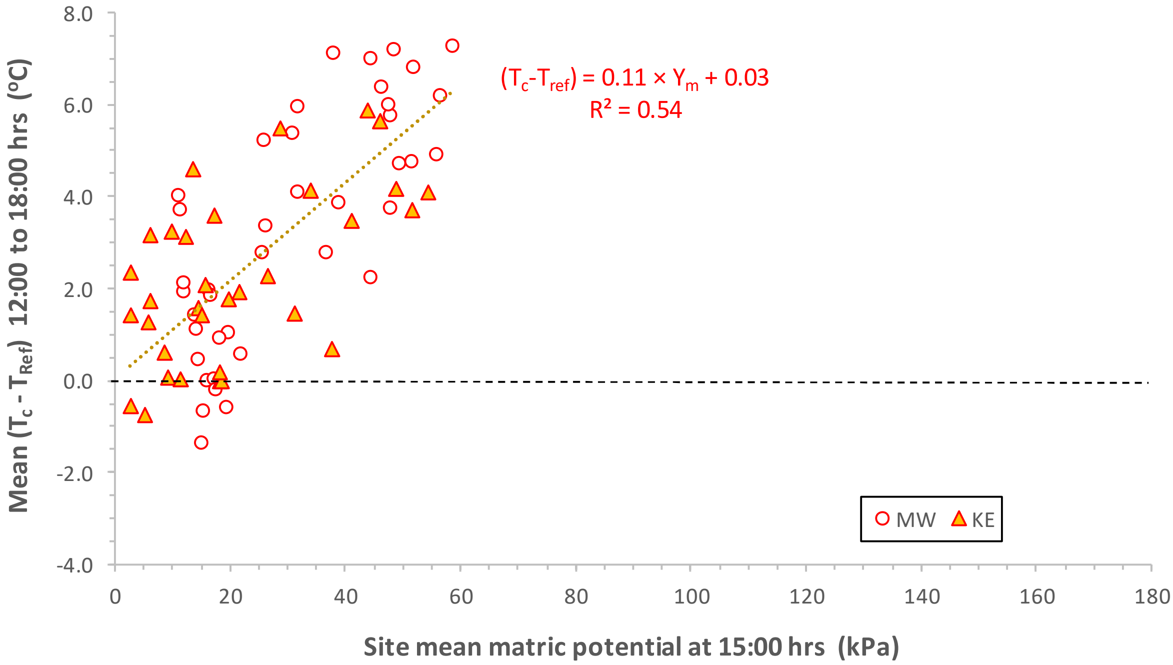

Figure 10. The relationship between average daily canopy minus air temperature (T_c-T_a) less the wet reference temperature ((T_c-T_a)$_{ref}$) from the three reference sites plotted against the mean matric potential (0-40 cm) in the centre of the bed at Sites MW and KE. The least squares line of best fit to the combined data from Sites MB and BA-7 is shown.

Canopy growth (inferred from NDVI) at Sites MW and KE was lower than at the three reference sites (Figure 6). If the high canopy temperatures at Sites MW and KE were due to stomatal closure, then the high canopy temperatures should be proportional to the reduction in biomass accumulation. Plotting the relationship between accumulated canopy temperature ($\sum T_c$) in the period 22nd January to 17th February against average NDVI in the period 800 to 1200°Cd (periods that were coincident for most sites) showed that accumulated canopy temperatures at Sites ME and KE were higher for their biomass compared to the other sites (Figure 11). This higher temperature may be due to the effect of the disease on the plant, or it may be due to changes in the canopy architecture brought about by the disease (e.g. the loss of individual leaves within plants, or the death of individual plants opening holes in the canopy where transpiration does not cool surfaces seen by the IR sensors). Given that NDVI provides a measure of crop green biomass and that both disease and water stress cause a reduction in biomass, the use of NDVI with canopy temperature may provide a useful tool for separating diseased crops from water stressed crops. This is not possible with just NDVI or temperature alone.

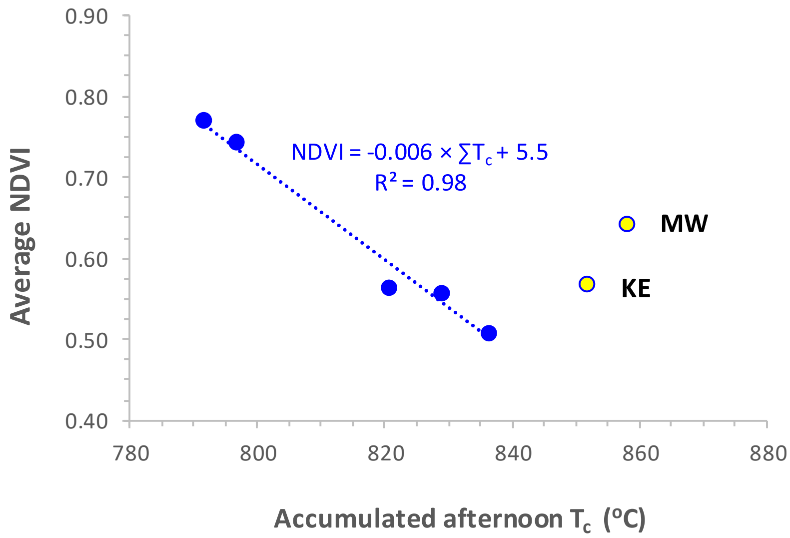

Figure 11. The relationship between average NDVI (800 to 1200°Cd) and average canopy temperature (12:00 to 18:00 hours) in the period from 22 January to 17 February at seven of the nine monitor sites. Sites WE and MB not included because of missing T_c data.

Tomato stomates close in response to flooding (Else *et al.*, 2009) and Riverine plains soils are waterlogged at matric potentials wetter than 6 kPa (North *et al.*, 2017) and tomatoes are water stressed at matric potentials drier than 50 kPa (Thompson *et al.*, 2007). These two matric potential thresholds were used to calculate the number of days that crops were either waterlogged or water stressed in January and February. Each hour during January and February that the average matric potential in the middle of the bed was less than 6 kPa or greater than 50 kPa was summed for each site and compared to red fruit yield. The relationship between accumulated days crops were either waterlogged or water stressed accounted for 81% of the variation in yield at eight of the nine sites (Figure 12), with yields reduced by 27 t/ha for each 10 days crops were waterlogged or water stressed. Yield at Site MW is thought to have been reduced more by disease than water excess or deficit.

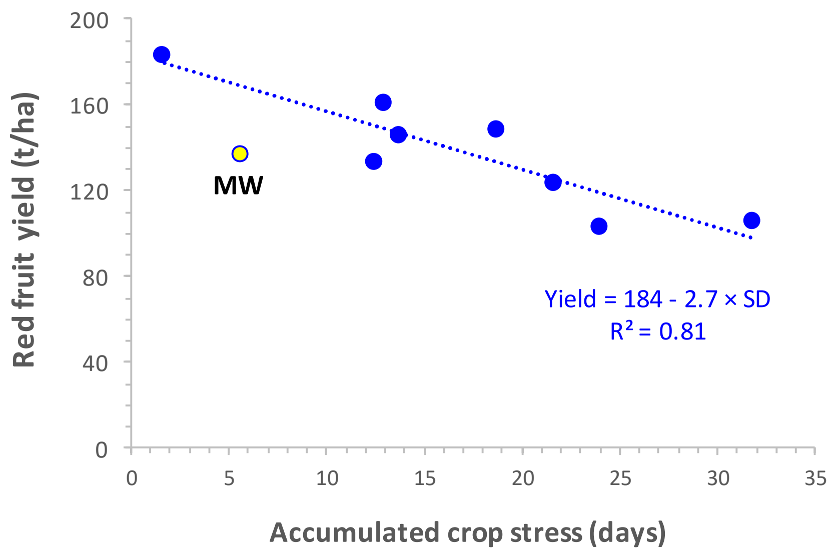

Figure 12. The relationship between red fruit yield at 94% moisture and the number of days the soil in the centre of the bed at each site was either too dry or waterlogged during January and February 2020.

Soil chemistry

Red fruit yield at 94% moisture was correlated with two soil chemical properties from both the December 2019 (Table 3) and May 2020 samplings (Table 4):

- Exchangeable aluminium percent (Al%) was negatively correlated with yield and the number of red fruit, and positively correlated with Brix
- Available potassium (K) was positively correlated with yield and the number of red fruit, and negatively correlated with Brix.

Yield was also significantly correlated with sulphur (S) in December and with pH, electrical conductivity (EC), ammonium-N and exchangeable calcium in May.

There was no significant correlation between yield or yield components with exchangeable sodium percent (ESP), chloride (Cl), phosphorous (Colwell) or nitrate-N concentrations.

Soil pH was significantly correlated with EC, ammonium-N, exchangeable Ca, cation exchange capacity (CEC), Al%, and available K in both the December and May samplings.

EC was correlated with nitrate-N, ammonium-N, exchangeable Ca, CEC, Al%, S and available K in the December samples, but not with nitrate or ammonium-N in the May samples.

Soil acidity (pH)

The soil samples taken in December showed that pH at the drip line was significantly lower than in the rest of the bed at five of the nine sites: the red loams at Sites BA-6, BA-7, MB, KR, and the grey clay at Site KE. Soil pH at the drip line fell significantly between December and May at Sites MW (a red loam) and WE (a grey clay), with pH_{CaCl} dropping from 7.1 to 4.4 at Site MW and from 6.3 to 5.1 at Site WE. By comparison, acidity in the rest of the bed at all the monitoring sites did not change significantly between the two sample dates, except at Site BA-7 where pH declined in the surface soil on the shoulder of the bed. The soil pH at the drip line was lower than in the rest of the bed at all monitoring sites in May, though this difference was non-significant at Site HE and due more to the fact that pH_{CaCl} rose in the rest of the bed at Site CH. (Figure 13).

Aluminium becomes soluble in soils when pH_{CaCl} is less than 4.5 and soluble aluminium is toxic to most crops at concentrations greater than 5% of exchangeable cations (Slattery *et al.*, 1999; Hazelton and Murphy, 2016). Aluminium in samples at the drip line at Sites BA-6, BA-7 and KR exceeded 30% of CEC in both December and May, with concentrations over 20 mg/kg, which is above threshold levels for even very acid tolerant plants (Slattery *et al.*, 1999). These three sites had the lowest growth rates of the nine crops (Figure 6) and the lowest three yields (if the yield for KR corrected for fruit size is used), so it might reasonably be assumed that the low yields were related to the very low pH and high Al% at the drip tape at these sites. However, the average pH of the soil solutions sampled from above the drip line at all sites on the 4th and 12th February was found to be 7.1±0.2 (n=11). This apparent difference arises because the pH of acid soils rises to 7 when they are saturated (Ponnamperuma, 1972), which is the pH around the drip tape these crops experienced during the irrigation season, whereas laboratory analysis of pH is done on samples that have been air-dried.

The very low pH at Sites BA-6, BA-7 and KR (Figure 13) is likely a factor in the low yields achieved at these three sites. It is also likely that it was the very low pH of the soil in the beds, rather than the low pH and high Al% around the drip tapes, that affected these yields.

Table 3. Results of the correlation analysis of soil chemical properties from samples collected in December 2019 and yield components. This analysis was done on site mean values for all parameters and was not split for soil location within the bed. Significantly correlated values are highlighted: p<0.5 level in orange; p<0.01 in green.

		pH ($CaCl_2$)	Electrical Conductivity *(dS/m)*	Nitrate Nitrogen *(mg/kg)*	Ammonium Nitrogen *(mg/kg)*	Exchangeable Calcium *(mg/kg)*	Cation Exch. Capacity *(cmol(+)/kg)*	Aluminium (KCl) *(% of CEC)*	Sulphur (KCl) *(mg/kg)*	Available Potassium *(mg/kg)*
pH ($CaCl_2$)	Pearson's r	—								
	p-value	—								
EC	Pearson's r	0.812 **	—							
	p-value	0.008	—							
Nitrate-N	Pearson's r	0.581	0.794 *	—						
	p-value	0.101	0.011	—						
Ammon-N	Pearson's r	-0.741 *	-0.671 *	-0.388	—					
	p-value	0.022	0.048	0.303	—					
Exch Ca	Pearson's r	0.99 ***	0.773 *	0.539	-0.679 *	—				
	p-value	< .001	0.015	0.134	0.044	—				
CEC	Pearson's r	0.962 ***	0.842 **	0.606	-0.725 *	0.968 ***	—			
	p-value	< .001	0.004	0.084	0.027	< .001	—			
Al % CEC	Pearson's r	-0.788 *	-0.699 *	-0.366	0.667 *	-0.745 *	-0.747 *	—		
	p-value	0.012	0.036	0.333	0.05	0.021	0.021	—		
Sulphur	Pearson's r	0.716 *	0.909 ***	0.695 *	-0.682 *	0.641	0.665	-0.6	—	
	p-value	0.03	< .001	0.038	0.043	0.063	0.051	0.087	—	
Available K	Pearson's r	0.889 **	0.782 *	0.451	-0.626	0.879 **	0.884 **	-0.714 *	0.684 *	—
	p-value	0.001	0.013	0.223	0.071	0.002	0.002	0.031	0.042	—
Brix	Pearson's r	-0.783 *	-0.771 *	-0.532	0.499	-0.764 *	-0.755 *	0.927 ***	-0.618	-0.664
	p-value	0.013	0.015	0.14	0.171	0.017	0.019	< .001	0.076	0.051
Red Fruit #	Pearson's r	0.718 *	0.694 *	0.261	-0.569	0.662	0.628	-0.83 **	0.739 *	0.827 **
	p-value	0.03	0.038	0.498	0.11	0.052	0.07	0.006	0.023	0.006
Yield @ 94%	Pearson's r	0.652	0.642	0.208	-0.522	0.593	0.529	-0.802 **	0.737 *	0.708 *
	p-value	0.057	0.063	0.592	0.15	0.092	0.143	0.009	0.023	0.033

Note. * p < .05, ** p < .01, *** p < .001

Table 4. Results of the correlation analysis of soil chemical properties from samples collected in May 2020 with yield components. This analysis was done on site mean values for all parameters and was not split for soil location within the bed. Significantly correlated values are highlighted: p<0.5 level in orange; p<0.01 in green.

		pH ($CaCl_2$)	Electrical Conductivity *(dS/m)*	Nitrate Nitrogen *(mg/kg)*	Ammonium Nitrogen *(mg/kg)*	Exchangeable Calcium *(mg/kg)*	Cation Exch. Capacity *(cmol(+)/kg)*	Aluminium (KCl) *(% of CEC)*	Sulphur (KCl) *(mg/kg)*	Available Potassium *(mg/kg)*
pH ($CaCl_2$)	Pearson's r	—								
	p-value	—								
EC	Pearson's r	0.81 **	—							
	p-value	0.008	—							
Nitrate-N	Pearson's r	-0.129	0.1	—						
	p-value	0.742	0.798	—						
Ammon-N	Pearson's r	-0.689 *	-0.545	0.066	—					
	p-value	0.04	0.129	0.866	—					
Exch Ca	Pearson's r	0.973 ***	0.735 *	-0.111	-0.609	—				
	p-value	< .001	0.024	0.776	0.082	—				
CEC	Pearson's r	0.962 ***	0.792 *	-0.141	-0.551	0.963 ***	—			
	p-value	< .001	0.011	0.718	0.124	< .001	—			
Al % CEC	Pearson's r	-0.798 **	-0.771 *	0.077	0.627	-0.749 *	-0.728 *	—		
	p-value	0.01	0.015	0.844	0.071	0.02	0.026	—		
Sulphur	Pearson's r	0.759	0.914 *	-0.23	-0.479	0.662	0.763	-0.65	—	
	p-value	0.08	0.011	0.661	0.337	0.152	0.077	0.162	—	
Available K	Pearson's r	0.9 ***	0.825 **	-0.154	-0.516	0.925 ***	0.938 ***	-0.761 *	0.792	—
	p-value	< .001	0.006	0.693	0.155	< .001	< .001	0.017	0.06	—
Brix	Pearson's r	-0.81 **	-0.887 **	-0.163	0.539	-0.786 *	-0.784 *	0.925 ***	-0.681	-0.81 **
	p-value	0.008	0.001	0.674	0.134	0.012	0.012	< .001	0.136	0.008
Red Fruit #	Pearson's r	0.768 *	0.774 *	-0.165	-0.745 *	0.747 *	0.71 *	-0.785 *	0.693	0.856 **
	p-value	0.016	0.014	0.671	0.021	0.021	0.032	0.012	0.127	0.003
Yield @ 94%	Pearson's r	0.718 *	0.729 *	-0.137	-0.719 *	0.682 *	0.622	-0.832 **	0.667	0.781 *
	p-value	0.029	0.026	0.725	0.029	0.043	0.074	0.005	0.148	0.013

Note. * p < .05, ** p < .01, *** p < .001

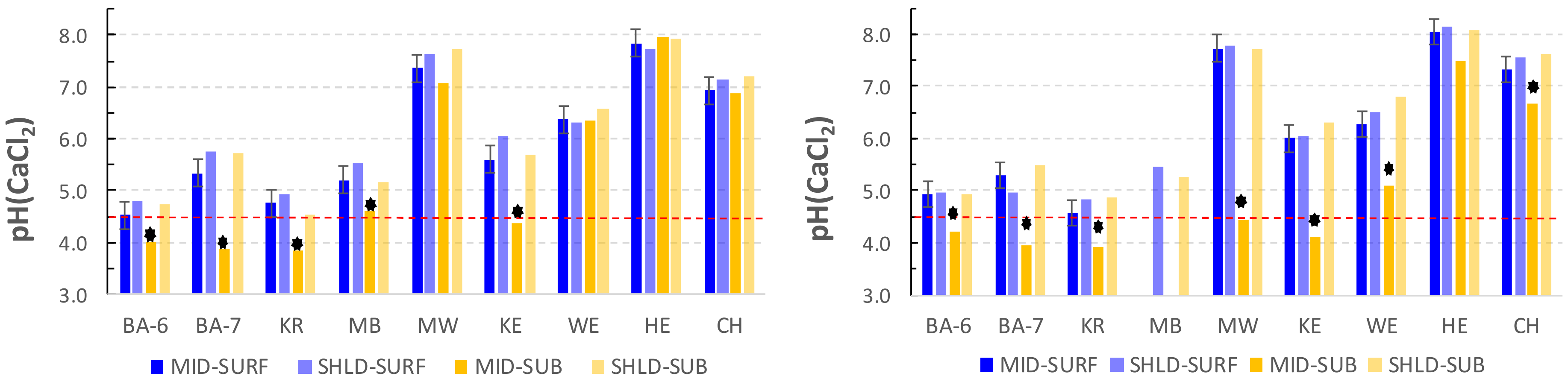

Figure 13. Soil pH_{CaCl2} in December 2019 (left) and May 2020 (right) from the surface (mid & shoulder of bed) and subsurface (drip tape & shoulder of the bed) at the nine monitor sites. Black asterisks show the samples from the drip line that had significantly lower pH than the rest of the bed. 95% confidence intervals are shown. The dashed line is the approximate pH_{CaCl2} at which Al toxicity commonly affects plants.

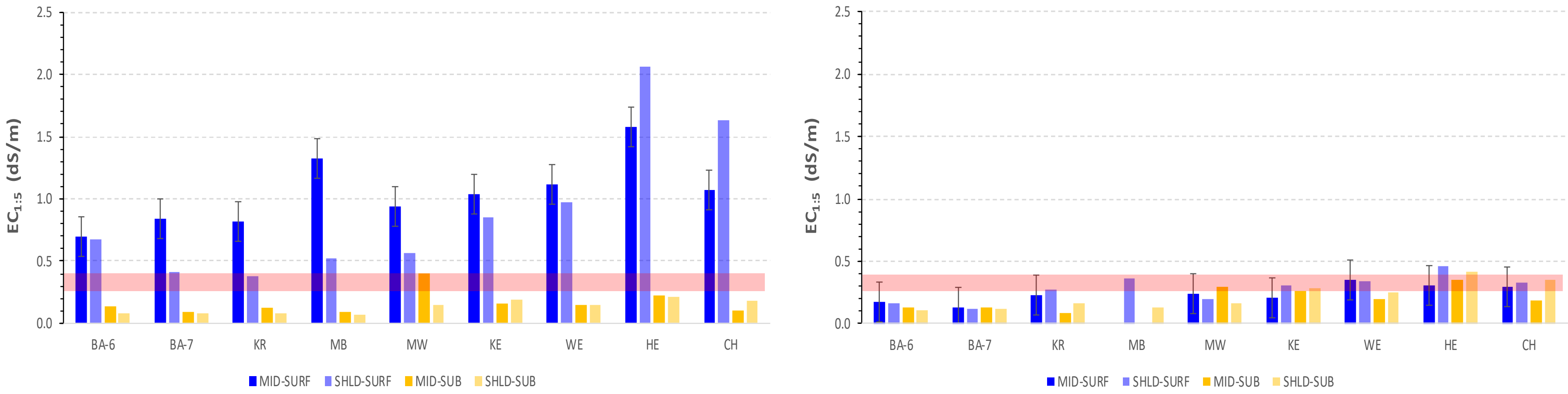

Figure 14. Electric conductivity (EC: dS/m) of soils sampled in December 2019 (left) and May 2020 (right) from the surface (mid and shoulder of bed) and subsurface (drip tape and shoulder of the bed) at the nine monitor sites. 95% confidence intervals are shown, and the broad red horizontal band is the threshold $EC_{1:5}$, above which plant growth is normally affected by (sodium chloride) salinity (Rengasamy, 2002).

Soluble salts (EC)

There was no correlation between electrical conductivity (EC) and chloride in the soil samples in either December or May. EC was, however, significantly correlated with nitrate-N, ammonium-N in December, and with Ca, S and K in both December and May.

The recommended threshold EC for healthy plant growth is 0.25 to 0.4 dS/m (Rengasamy, 2002), so at first glance the exceptionally high EC values from the middle of the bed in December appear toxic (Figure 14 left). However, a major portion of the EC in December was contributed by nitrate-N, with lesser contributions from ammonium-N, Ca, S and K. The high EC in December is thus due to the fertiliser applied to these crops through the drip line, and EC fell in May to more normal levels is because fertigation had ceased and rain in April leached these soluble salts out of the beds (Figure 14 right).

An insight into the pattern of water movement in the beds during and after the season is provided by the EC measurements, which highlight some major differences between the soils at the nine sites. It can be seen in Figure 14 that there was a high concentration of soluble salts in the surface of the beds at all sites in December. At all the red loam sites except Site BA-6, the concentration was higher in the middle of the bed than it was at the shoulder. This was similarly the case at two of the grey clays, Sites KE and WE, but the difference between the middle of the bed and the shoulder was smaller. In the other two grey clays at Sites CH and HE, however, the concentration of soluble salts was lower in the middle of the bed than it was at the shoulder. These two sites also differed from the other six sites in that the concentration of soluble salts in the surface of the beds was higher.

These patterns in the distribution of EC are reflected in those of nitrate-N (Table 5). Given the similarity in the amount of water and nitrogenous fertiliser applied to these sites (Table 1), these patterns in the distribution of soluble salts will reflect water movement in the beds at these sites. The higher EC values in the surface of the beds at Sites CH and HE indicate greater upward flows from the drip tape and hence lower deep drainage losses. Conversely, the lower EC values in the surface soil at the red loam sites, particularly BA-6, BA-7, KR and MW indicate a greater downward movement of water from the drip tape. In addition to this, there is less lateral movement of water at these sites, so the shoulders don’t accumulate soluble salts. The grey clays are known to be better subbing soils, and this is seen in the higher ECs in the shoulders of the beds at Sites KE, WE, CH and HE, with the soils at CH and HE having better subbing properties than those at KE and WE.

Application of soluble fertilisers, leaching of nitrate, and acid flushing of drip lines have been suggested as the reason for the decline in pH around the drip tape (Barber *et al.*, 2001). Given the similarity in the amounts of fertiliser applied and assuming maintenance of drip lines is also similar, then the observed differences in the distribution of soluble salts and nitrate in the beds points to the loss of nitrate as the major factor behind low pH. Roughly 300 kg of N/ha is applied to these crops at a depth of around 25 cm through the drip tape in the form of ammonium, urea and nitrate. The soil at the emitter is saturated for much of the irrigation season and anoxia was observed in this saturated zone. Some of the applied ammonium will nitrify in the aerobic zone outside this saturated zone and the nitrate produced may then be lost either through leaching, or through denitrification and gaseous loss with water moving upwards to the soil surface. The magnitude of the reduction in nitrate-N in the surface of the beds at all sites between December and May suggests these losses may be significant (Table 5).

Table 5. Average nitrate-N concentrations (mg/kg) for the two groups of soils (red loams and grey clays) at the four sample locations in the beds in December 2019 and May 2020.

Soil type	Sites	Depth	December		May	
			Mid-bed	Shoulder	Mid-bed	Shoulder
Red loam	BA-6, BA-7, KR, MB, MW	Surface	225	132	39	39
		Sub	52	14	29	17
Grey clay	KE, WE	Surface	198	192	36	43
		Sub	39	15	33	19
Grey clay	HE, CH	Surface	224	358	35	16
		Sub	11	6	15	27

Soil structure

A key indicator of soil stability under irrigation is its propensity to disperse. Emmerson dispersion tests were conducted on three of the red loams (Sites BA-6, BA-7 and MW) and one of the grey clays (Site WE). While all samples from both the surface and sub-soil from these sites exhibited some degree of slaking, none of them dispersed. This was despite some surface soil samples from Sites BA-6 and BA-7 having exchangeable sodium percentages of 12% and 9.4% respectively. Soils with high soluble salt concentrations will not disperse because of an electrolyte effect, so the high EC of soils during the irrigation season may confer a degree of stability in these subsurface drip irrigated systems. The influence of soluble salts on sodium levels in soils during the irrigation season is seen in the exchangeable Na-EC relationship from the December samples (Figure 15). Any effect on soils from rising Na will most likely be counteracted by the commensurate rise in EC.

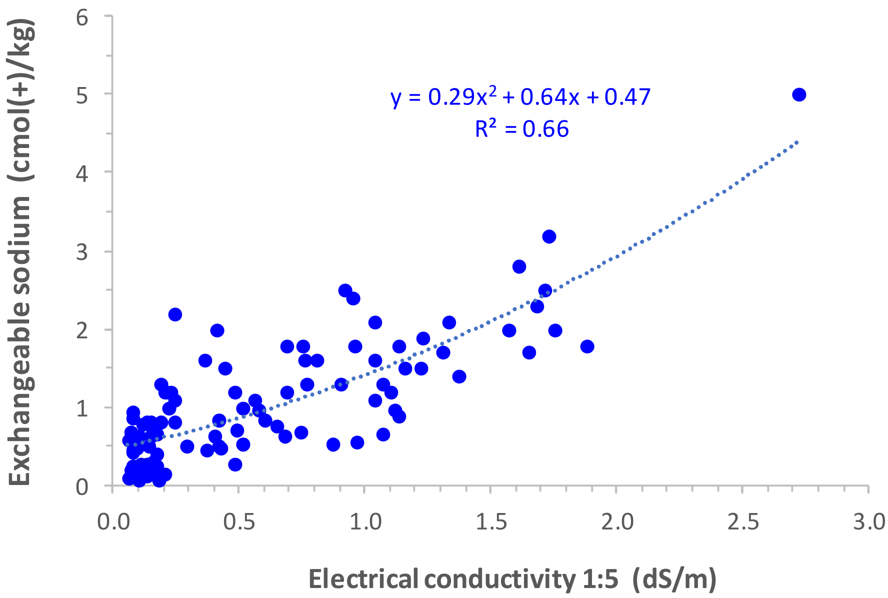

Figure 15. The relationship between soil electrical conductivity (dS/m of a 1:5 soil:water solution) and exchangeable sodium (cmol(+)/kg) in soils at the nine monitor sites in December 2019.

Bulk density and compaction

Bulk density measurements showed differences between the two soil types. The grey clays (Sites HE, CH, KE and WE) had generally lower bulk densities in the surface soil in both the middle and shoulder of the bed and, in line with their self-mulching properties, density at some locations decreased between December and May with no cultivation. Bulk density in the surface of the red loams was generally higher in both the middle and shoulder of the bed, and it increased between December and May (Figure 16). Three of the red loam sites had been cultivated prior to sampling in May. Sampling for bulk density was not done at Site MB because of this, but undisturbed locations were found at Sites KR and MW.

Bulk densities in the sub-soils at all sites were higher at the shoulder than in the middle of the bed and indicate a degree of compaction in the bed shoulder at all sites (Figure 17). The difference between the middle and shoulder of the beds was greatest at Sites BA-7 and KR. Nevertheless, the bulk densities of all samples were within the optimal range for tomatoes (Aumann *et al.*, 1999) and should not have been limiting to water movement or root growth.

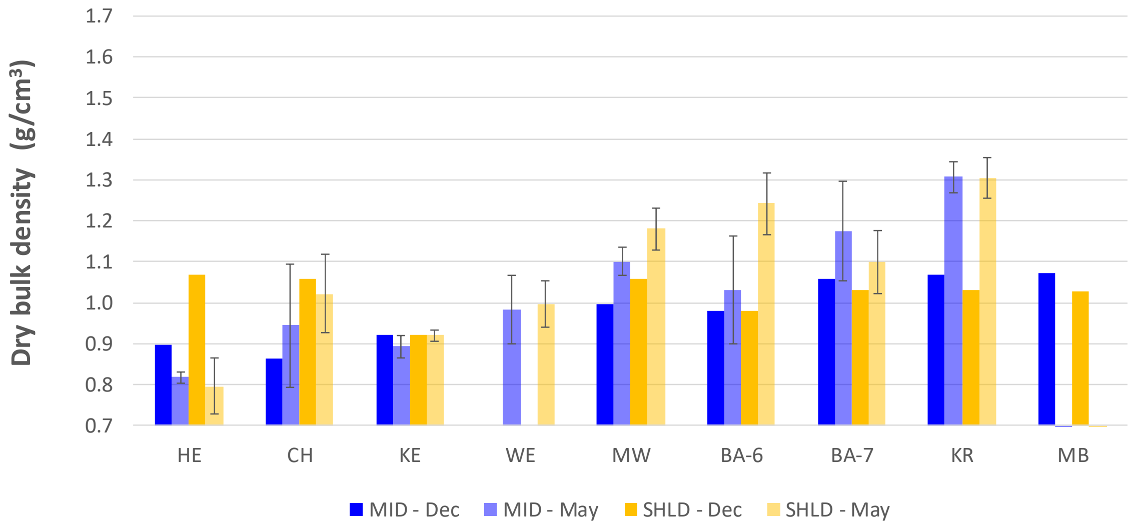

Figure 16. Dry bulk density (g/cm^3) of surface soils from the middle and shoulder of beds at the monitor sites in December and May. Error bars = standard error of the mean (n = 6).

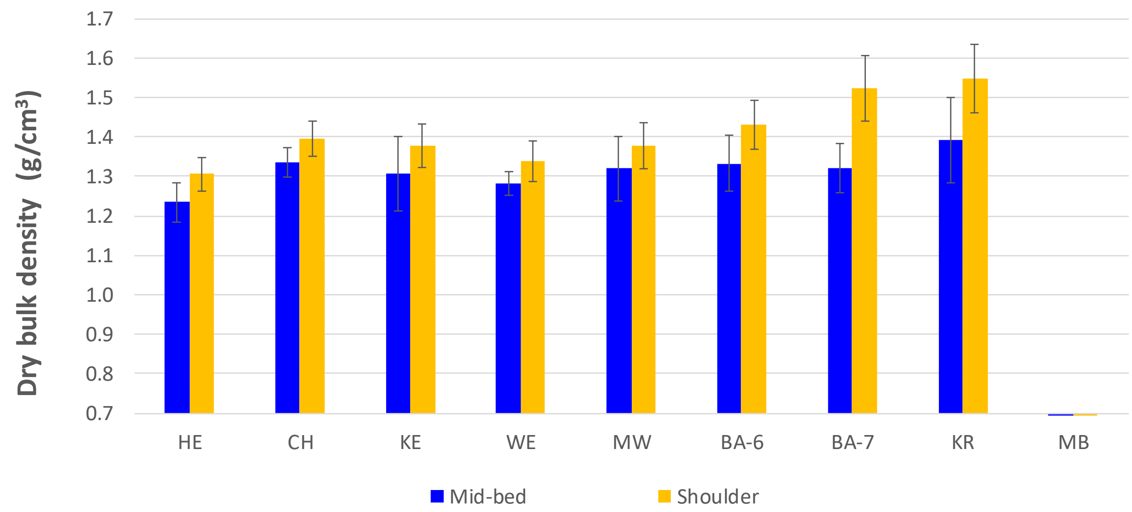

Figure 17. Dry bulk density (g/cm^3) of sub-soils sampled in the middle and shoulder of beds at the monitor sites in May 2020. Error bars = standard error of the mean (n = 6).

Soil penetration resistance measurements showed no evidence of compaction in the centre of beds except at Site KR, which had by far the hardest soil of all the nine sites (Figure 18). Site BA-6 had lower soil strength in the centre of the beds compared to Site BA-7 and KR. These three sites had the same cropping rotation over the past four years and were on similar soils and the difference may be due to the ripping at Site BA-6 in spring 2019. However, this cannot be definitively concluded without a comparative "before" sample. Evidence of compaction from tractor passes to prepare and sow the 2020 winter crop can be seen at Sites MB, KR and BA-6. Similarly to the bulk density measurements, the grey clay sites (left side of Figure 18) had generally lower soil strength than the red loams (right side of Figure 18).

Soil strength changes with soil moisture content, so it is not possible to say definitively whether these differences are due to compaction or to differences in moisture content. However, management did create a difference between the two soil groups, as the red loam soils at Sie MB, MW, KR and half of BA-6 were all disced, the beds knocked flat and a winter crop sown prior to sampling in May. The influence of this is seen in the contour plots from these sites, with greater penetration resistance under the wheel tracks from these operations (under the furrow at 5.54 m at Site MB and at 4.56 and 6.08 m at Site KR) and less depth of low strength soil in the centre of the beds.

Hydraulic conductivity

The well permeameter measurements in May showed yet another difference between the two soil types. The grey clay sites had more consistent hydraulic conductivities and there was less variability within each site. Standard errors as a percentage of the means in the grey clays were roughly half that of the red loams. This difference is considered to be due to a more homogeneous structure and uniform subbing in the grey clays. Flow in the red loams, on the other hand, is dominated by crack flow which is, by its nature, clustered and spatially more variable.

The potential for very high hydraulic conductivities in the red loams is seen at Site MW and BA-7. Rain fell during the measurement period at Site CH and this affected those readings.

Table 6. Saturated hydraulic conductivities (mm/day) measured using well permeameters just off the centre of the beds and at the depth of the drip tape at the nine monitor sites in May 2020.

Soil type	Site	Mean K_{sat} *(mm/day)*	number of readings	Standard error	s.e. as % of mean
Grey clay	HE	554	6	132	24%
	CH	19 *	4	5	27%
	KE	668	6	180	27%
	WE	464	6	77	17%
Red loams	MW	950	6	383	40%
	BA-7	2,100	5	1,054	50%
	BA-6	131	6	73	56%
	KR	485	6	251	52%
	MB	121	5	62	51%

* readings at Site CH were affected by rain

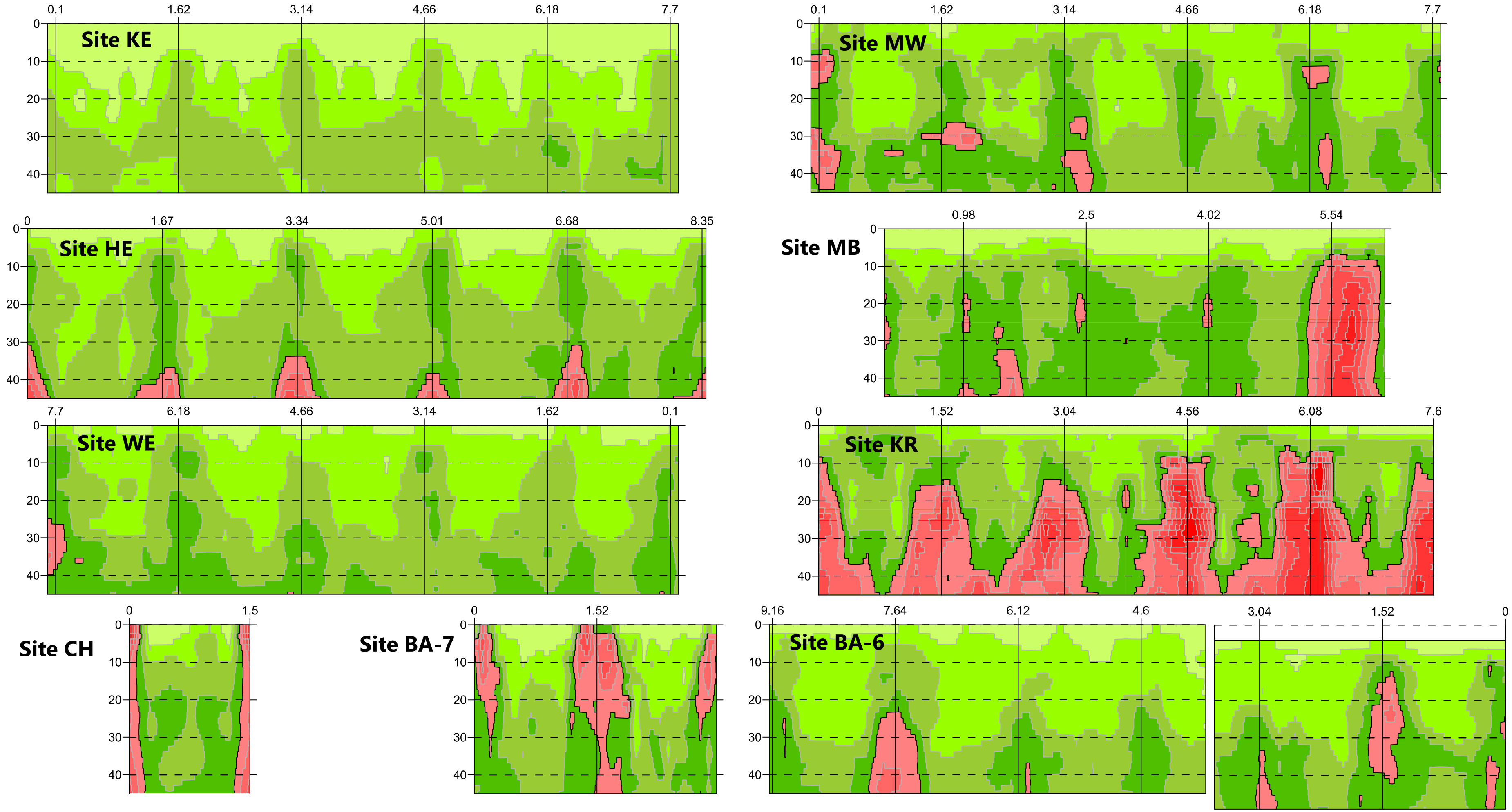

Figure 18. Contour plots of penetration resistance (kPa on y axes) to 0.45 m depth along transects across five beds (x axes) at the nine monitor sites in May 2020. Two transects were done at Site BA-6: one across 4½ intact beds (Site BA-6 left) and a second across 2½ beds which had been disced to pull the beds down and fill in the furrows (Site BA-6 right). Increases in penetration resistance are shown by an increase in shade from light to dark, with soil having a penetration resistance greater than the limiting value for root growth of 2500 kPa shown in red. The position of furrows is indicated by the vertical lines in each contour plot.

Discussion

A 200 t/ha target

A benchmarking study in the mid-1990s estimated the theoretical physiological potential of processing tomatoes based on solar radiation to be 172 t/ha in the eastern Murray valley, 194 t/ha in the western Murray valley, and 201 t/ha in the Murrumbidgee Irrigation Area (Beecher *et al.*, 1995). While it is recognised that higher yields are needed to ensure profitability in the face of rising water prices, setting a yield target of 200 t/ha may not be appropriate if it is not physiologically possible, particularly in the eastern Murray valley. Additionally, just as differences in temperature and solar radiation regimes create differences in physiological potential yields between regions, so there will be differences between years.

An example of the consequences of this is seen in the irrigated grains industry, where advisory services have promoted a 10 t/ha yield target based on trial yields. An examination of the physiological potential for wheat in the southern Murray-Darling basin, however, showed the median physiological potential yield was only 9 t/ha, with yields of 10 t/ha being at the upper quartile. Thus, whilst 10 t/ha of wheat is achievable, it is only achievable in 25% of years, so setting such a high yield target may encourage growers to apply inputs in excess of what can be reliably achieved.

The other difficulty with the 200 t/ha target is the reporting of yields at field moisture contents. Yields should be corrected and reported at a standard moisture content so the effect of environment and management on fruit solids and sugar content can be assessed and compared, free of any bias from water content. For example, two 140 t/ha crops having fruit moisture contents of 93% and 94% will have dry matters of 9.8 and 8.4 t/ha respectively. This translates to yields of 163 t/ha and 140 t/ha if both are reported at a moisture content of 94%. This will allow true efficiencies of water use and radiation capture to be found. Additionally, it allows for a better comparison of trials across sites and years and ensures better selection of varieties/techniques that move the industry towards higher yields.

The industry used to benchmark through the TomCheck program (Aumann *et al.*, 1999; Hickey *et al.*, 2001). It no longer appears to do so, most likely because the costs of running the program are higher than the perceived benefits. Nevertheless, without benchmarking it is not possible to track whether the industry is making progress towards achieving their target (i.e. 200 t/ha), nor is it possible to differentiate management actions that improve and impede progress towards that target. Water benchmarking is done by both the cotton (https://www.cottoninfo.com.au/publications/water-irrigation-benchmarking) and rice industries, with the SunRice MapRice program being of potential greatest relevance to the processing tomato industry (https://corporate.sunrice.com.au/media/683673/maprice-gis-user-guide.pdf). At a bare minimum, collecting yield data linked to blocks would allow long term monitoring to detect trends and assess progress towards a benchmark target yield. In addition to this, the use of IrriSAT (Hornbuckle *et al.*, 2016) would allow yields to be correlated with canopy growth and crop potential water use in a cost effective way.

Soils

Loss of structure and soil compaction around drip lines due to constant wetness and migration of cations and clays away from emitters has been posited as likely to reduce hydraulic conductivity and pore volume around drip-lines under long-term use of subsurface drip systems and be a cause of long-term yield decline in tomato blocks (Barber *et al.*, 2001; Yong *et al.*, 2015; Quach, 2017; Lanyon and Kelly, 2010).

Soil acidity around the drip tape has also been implicated, particularly with regard to disease (Quach, 2017; Ajith, 2019). In response, these studies investigated potential solutions to acidification and structure loss with the aim of lifting yields. However, a causal link between these observations and a decline in yield was not made and yield increases from applied treatments did not eventuate.

Calcium to improve structure

The application of calcium in gypsum is advised if soils disperse in response to high sodium levels on exchange sites. There is no evidence that sodium and high ESP was an issue in the blocks monitored in this study, so gypsum application to these soils would have no beneficial effect on structure. Some samples collected in December had high ESPs (>6%), but the correlation between exchangeable sodium content and EC indicates that these high ESPs were due to high soluble salt contents in the irrigation water during the irrigation season. High salinity and the attendant electrolyte effect should have ensured soil stability through the irrigation season, and low ESP levels in the centre of the bed in May (< 6%) also indicates that dispersion is unlikely to affect water distribution from the drip tape at these sites.

ESPs were higher in May in the subsoil at the shoulder of the bed at five sites (Sites BA-6, BA-7, KE, KR, and HE). There is the potential for this to affect soil structure at the edges of the bed in the longer term when combined with compaction from wheel trafficking of furrows. However, the cation composition on exchange sites will reflect the cation composition of the soil solution, so managing sodium should be easily achieved in a fertigation program.

Soil acidity

Conventional soil sampling and analysis showed that pH at the drip tape was lower than in the rest of the bed. Measurements of soil matric potential and redox potential showed that the soil zone around the drip tape is mostly saturated and often anoxic during the tomato growing season. The pH of acid soils increases with soil water content and goes to neutral when soil is saturated (Ponnamperuma, 1972; Husson, 2013). This was confirmed by the data from the soil solution extracts, which showed the pH near the drip tape at all sites was around 7 during the irrigation season. Because subsurface drip irrigated crops generally grow in high moisture content soils, the low pH and very high Al% measured in the air-dried soil samples taken from near the drip tape is unlikely to affect yields in such crops.

In-crop management of pH should (and hopefully does) occur through the management of pH in the fertigation program. Where low pH is a problem, alkalising fertilisers will increase pH without the need to apply additional carbonates such as lime. For instance, potassium-nitrate has a pH of 8-9 as a 1% w/w solution. Calcium-nitrate, on the other hand, would assist in displacing excess sodium if sodicity was an issue whilst having the potential to increase pH due to nitrate uptake (Tang and Rengel, 2002). The ability to manipulate soil solution chemistry through fertigation thus gives these subsurface drip systems the capacity to manage most soil chemical problems.

Soil chemical benchmarks and monitoring techniques from dryland systems are not strictly applicable to these systems because of the amount of water and fertiliser applied to them. Interpreting soil tests in the same way as for dryland soils is not appropriate in these industrialised soils unless a causal link between measured properties (pH, EC, ESP) and yields can be demonstrated. While there were positive correlations between yields and pH and EC in May, there is no evidence that either low pH or low EC was the cause of low yields *per se*.

Deep ripping to improve structure

Site BA-6 was deep ripped and new tape installed in 2019. This block was next to Site BA-7 and on the same soil type. While the cone penetrometer readings show that soil strength was lower in the beds in the ripped block (BA-6 compared to BA-7 in Figure 18), there was no difference in yields between the two Sites (103 *cf* 105 t/ha: Table 2). The soils at Site KR and BA-6 were similar and these sites had the same cropping history and management over the previous four years. The soil at Site KR was compacted at the edge of the beds and soil strength was slightly higher around the drip tape, yet it achieved a higher yield: 13 t/ha more if yields are compared based on fruit number, or 30 t/ha more if fruit size is ignored.

The evidence from this one site is by no means conclusive. However, the assumption that low yields in irrigated crops are caused by observed soil compaction needs better evidence before ripping is advocated as a 'cure'. High strength and low non-limiting water range has been observed in a wide range of irrigated Riverine plains soils, but this has not been shown to have any bearing on yields because yields are primarily determined by irrigation management (North, 2018). Deep ripping should only be done to deconsolidate soils that have been clearly shown to be compacted, and it will only be effective for any length of time if the soil does not slake or disperse. For instance, deep ripping to remove a hard pan in an alluvial silty, fine sandy loam at Carnarvon with very low total soluble salts (<0.005%) had no effect on tomato yield (Muller, 1993). This was because the low clay content and very low electrolyte effect result in weak forces binding soil particles together, so there is little to resist soil consolidation when wet. Ripping does not increase these forces, so it was ineffective, whereas gypsum application improved aggregate flocculation by increasing the electrolyte effect, and better irrigation management to remove water deficits increased yields.

Guidelines for ripping of soils to remove hardpans and compaction in Australian soils have been published (Armstrong *et al.*, 2009). It is not a technique suitable for all soils, particularly sodic soils. Nor is it a technique suitable for long term management of irrigated soils because of their propensity to re-consolidate under repeat wetting and drying cycles (McKenzie *et al.*, 1987; Cockroft and Olsson, 2000). A considerable amount of work has gone into finding ways to improve the physical properties of irrigated red-brown earth soils in the Murray-Darling basin (Adem and Tisdall, 1984b; Adem and Tisdall, 1984a; Tisdall and Adem, 1987; Hall, 1990). The key thrust of this work was to build organic matter in these lighter textured soils to improve aggregate stability, water movement and subbing. The distribution of soluble salts in the beds on the red loam soils observed at the monitor sites is indicative of poor subbing compared to the grey clays. Thus, developing rotation and cultivation practices that build organic matter offers greater prospects for yield improvement and stability for subsurface irrigated tomatoes on red loams than does indiscriminate ripping.

Disease

There is not much that can be inferred about the influence of disease on crop yields because it could not be assessed after Melbourne University's laboratory closed due to COVID-19. However, by way of comment, developing a system capable of continuous tomato production is unlikely to be a successful strategy for increasing yields over the long term. Lack of diversity in both space and time in such a system will leave the industry susceptible to the build-up of weeds, pests, and diseases and make growers more reliant on technological interventions than they are at present. Such a system would leave the industry vulnerable to shocks, and a monoculture may in fact be less profitable than a more diversified cropping system. Corn-soybean rotations, for instance, have less risk than corn monoculture practices, with risk reduced by diversification, higher yields and reduced costs (Helmers et al., 2001).

The sugar cane industry also had problems with yield decline, and it was suspected to be largely due to growing cane in a long-term monoculture. A one-year fallow break was investigated, both with and without fumigation. Yields of first and second-year crops following the break were increased by 42 and 18% respectively in fumigated paddocks, and by 27 and 30% with the break alone. Yield Increases were longer lived without fumigation. Rather than a fallow break, if the fourth-year cane crop was replaced with a grain legume or maize crop, then yields increased over the following three cane crops by approximately 20%. (Garside and Bell, 2011). A similar investigation is needed to find more profitable, lower risk rotations for the processing tomato industry.

A postulated mechanism for low yields on red loam soils

This study has not taken a deductive approach and tested any theories about the cause of low yields in the processing tomato industry. As such, it is not possible to say definitively that soil acidity, poor structure, or disease are or are not prime causal agents; nor that ripping will or will not work. Rather, an inductive approach has been used to collect data to better inform theories about the cause or causes of low tomato yields. Based on this data it is possible to highlight several pieces of evidence that point to possible causal factors.

- NDVI is a good measure of canopy size (Kalaitzidis *et al.*, 2010) and NDVI between 800 and 1200 °Cd was closely correlated (R^2= 89%) with yields from the nine sites.
- Biomass accumulation and transpiration are linearly related (Tanner and Sinclair, 1983; Ritchie, 1983), so the smaller canopies must have used less water.
- The canopy temperature data indicates disease was a factor in reducing canopy size at two of the sites (KE and MW). Water use by these two crops would have been reduced in line with the reduction in canopy size.
- The negative relationship between accumulated stress days and yield shows that the lower yielding sites were waterlogged and/or water stressed. Stomatal closure in response to root signals during these times (Else *et al.*, 2009) will have reduced water use by these crops.
- Similar amounts of water and fertiliser were applied to these crops, so the observations regarding the differences in the distribution of soluble salts within the beds between the two soil types fits with known wetting pattern differences between lighter textured and heavier textured soils (YARA, 2018).

- Lower concentrations of soluble salts in the surface of the beds in the red loams in December indicates less upflow from the drip tape. The effect of different planting dates is not accounted for by this.
- The lower concentration of soluble salts in the shoulders of the beds in the red loams indicates smaller lateral flows than in the grey clays.

It is inferred from the above that:

1. a greater proportion of the water applied to the red loam soils was lost in deep drainage;
2. a greater proportion of soluble fertiliser, particularly nitrate, was leached below the root zone in the red loam soils, with roots unable to access the deeper profile below the drip line because of waterlogged and reduced conditions.

Yields may be lower in red loam soils because their coarser texture, and lower proportion of fine pores means water does not move upwards and outwards from the emitter to the same extent as it does in the finer textured grey clays. Yields may be generally lower in these soils because a greater proportion of the fertiliser applied to them is lost in deep drainage.

This might be confirmed by monitoring soil solution chemistry and water fluxes in the bed during the irrigation season to assess water and N losses.

Computer modelling of the effect of emitter rate, spacing and depth would help shed light on the likelihood of this being an issue and provide information about possible solutions.

Major yield limiting factors

Site CH had the highest yield and no major issues were identified as affecting this crop. For the other eight crops, four issues were identified as affecting yields:

1. **Harvest losses**

   Site HE was largely unaffected by any major impediment through the season, but picking was delayed and this resulted in high harvest losses. Site WE was also largely unaffected by major impediments through the season, but late planting pushed harvest into April and rainfall before picking resulted in high losses in rotten fruit.

   The industry is aware of this issue and strategies such as breeding for extended field storage are in place. There are limits to what is logistically possible at harvest time, but the fact that the growers reported harvest delays of 7 to 14 days at six of the nine sites makes this a significant issue to overcome if the industry is to achieve its target of 200 t/ha. Techniques such as dipping in calcium chloride or modified atmosphere packaging (Arah *et al.*, 2016) may allow fruit to be picked on time and stored in the paddock to ease logistical bottlenecks during harvest and are worth investigating.

2. **Disease**

   Site KE and Site MW were affected by disease. At Site KE, the disease was coincident with waterlogging, whilst the disease at Site MW is attributed to the fact that the crop was the third tomato crop in a row.

   The industry is also aware of this issue and strategies such as breeding for disease resistance and Metham sodium soil fumigation are major control agents. The lack of a profitable rotation crop is seen as an impediment to moving away from a tomato monoculture towards a more sustainable approach to the long-term management of disease. Additionally, the issue of poor subbing in red soils will not be solved whilst beds are so heavily disturbed when placing Metham sodium because cultivation results in the loss of organic matter and the root mass that is so essential for aggregate formation and stability in these lighter texture soils. As well as the development of profitable crop rotations, alternative technologies are needed to place Metham sodium in these soils with minimal soil disturbance, or to enable its use to be reduced.

3. Water management

- Site BA-6 was waterlogged on 33% of days in January and February. The low hydraulic conductivity measured at this site may have been a factor in this.
- Site BA-7 was water stressed on 96% of days in January and February. The very high hydraulic conductivity at this site may have been a factor in this.
- Site MB was largely unaffected by any major impediment until around 800°Cd (29th December), but was waterlogged and water stressed on 21% and 12% of days respectively in January and February. The low hydraulic conductivity at this site may have been a factor.

Changing the water supply to a crop by altering the design and/or management of an irrigation system is achievable. In comparison, changing the supply of water to a crop by altering the soils physical properties is very difficult and uncertain, particularly as this is largely determined by clay content and type.

Crop managers do not appear to use soil monitoring technology to schedule and monitor irrigations. When soils are familiar and the behaviour of paddocks to irrigation is known, such technology may not be warranted. However, when problems arise, they are invaluable tools to ensure the right amount of water is applied on time.

Work is currently being undertaken at Kilter Ag in Swan Hill by CSIRO to develop real-time sensing and control of drip irrigation in tomato and cotton using thermometry (Brodrick and Bange, 2018). While this work may benefit the industry, it should be noted that lower cost, simpler and equally effective technologies already exist (http://insidecotton.com/xmlui/handle/1/4668). It should also be noted that high canopy temperatures can be caused by more than just water stress (e.g. disease, as found in this study), so it may not be a reliable method for scheduling in tomato.

Simpler, low cost alternatives for scheduling irrigations and monitoring soil water and fertigation are recommended:

a. Matric potential sensors have been shown to accurately define soil water thresholds for scheduling irrigations in tomatoes (Thompson *et al.*, 2007). These sensors can also indicate the occurrence of waterlogging.
b. IrriSAT is freeware that uses the Google Earth platform and Landsat imagery to track crop NDVI and predict water use based on canopy cover and potential evapotranspiration (Hornbuckle *et al.*, 2016). The method has been used to schedule irrigations in tomatoes (Marta *et al.*, 2019) and can be considered reliable, as tomato canopy size is a good indicator of crop water demand (Cetin and Uygan, 2008).

c. Soil solution samplers can provide information about losses and efficiencies of fertiliser applications (Falivene, 2008; YARA, 2018). Their use in combination with matric potential sensors should lead to improvements in both water and fertiliser application efficiencies.

Work is also needed to better match drip systems to the soils they are located in. A 'one size fits all' approach does not work and irrigation systems need to be designed to suit the soil type, not the other way around. Computer models (e.g. HYDRUS) can simulate water and solute flows in subsurface drip irrigation systems and simulation modelling is a cheaper and more effective way of assessing the effect of multiple variables on irrigation system performance than field trials. Modelling should be done to determine the emitter rates, spacing and placement depth that best suits red loam soils. In addition, modelling of water and fertiliser movement should be used to investigate what improvements could be made to irrigation and fertigation practices to improve water and fertiliser efficiencies.

4. Soils

Site KR was possibly affected by the compaction observed at that site and it was waterlogged on 16% of days in January and February.

Whilst it is generally easy to attribute lower than expected yields to observed poor soil structure in dryland settings, it does not necessarily follow in irrigated systems. Soils with poor structure are less productive in dryland situations because less water enters, they hold smaller volumes of water, and the water within them flows at slower rates. The causal link between structure and yield does not strictly apply in irrigated systems because the deficiencies of the soil are (or should be) overcome by the irrigation system. Consequently, soil amelioration in irrigated systems may not change yield because it doesn't change the availability of what drives yield, namely water. Because of this, it is more effective (and easier) to change irrigation management or modify the irrigation system than it is to modify the soil. Modifying the soil, on the other hand, and expecting a change in structure to improve water supply in the face of possible poor irrigation practices is unlikely to yield a positive outcome.

The soils used in these subsurface drip irrigation systems should not be viewed in the same way as dryland soils, or even in the same way as other broadacre crops that are surface or sprinkler irrigated. Firstly, the volume of water applied these soils is large: the 8 ML/ha applied to the paddock may be more like 24 ML/ha given an emitter spacing of 0.50 m and a wetted area that is a third of a 1.52 m bed width. Secondly, a large amount of fertiliser is applied to the crop, it is soluble, and it is applied in the irrigation stream directly to the soil in the bottom of the root zone. Water and nutrient deficiencies in these systems are therefore most likely to be management related, not soil issues. Furthermore, soil chemistry is overwhelmingly dominated by the cations and anions applied in the irrigation stream, so any deficiencies (e.g. low pH, ESP) are easily addressed by changing the fertilisers that are applied. This is not to say that soil chemistry or structure is not an issue. Rather that it is a secondary issue that should be examined only after system design (i.e. match systems to soil types) and water and fertigation management has been rectified.

The key soil issue is not structure *per se*, but soil type. The grey clay soils are known to be good summer cropping soils because of their good physical properties and stability under irrigation (Hughes, 1999). Apart from one site affected by disease and waterlogging, growth of crop canopies on this soil type suffered no setbacks. By contrast, the red loam soils are known to have lower aggregate stability in irrigated cropping systems (Murray and Grant, 2007). This is because their lower clay content makes organic carbon a major contributor to aggregate stability and much organic carbon is lost when these soils are tilled in intensively cropped, irrigated systems (Adem and Tisdall, 1984b). Aggregates that are unstable under wetting coalesce and soil porosity is reduced. This reduces soil water holding capacity, as well as water movement into and through the soil. Every red loam site suffered periods of waterlogging and/or water stress which reduced canopy growth.

Rather than looking to reduce compaction, increase pH, add calcium, or pump in oxygen, efforts in these red loam soils should be directed to improving soil stability and aggregate formation. This will only be done by increasing soil carbon levels and moving away from practices that work counter to the formation of good structure Two areas for improvement are identified:

a. <u>Rotations</u> - the issue of disease in a monoculture and the benefits of rotations has been discussed. There are also benefits to soil structure. Bare fallows are not conducive to the formation and maintenance of good structure in red loam soils and should be avoided (Hall, 1990). Adding fibrous rooted crops to the rotation creates soil structure in red loams through the physical binding of soil by roots (Tisdall and Oades, 1979).
b. <u>Cultivation</u> – aggregate stability in Riverine plains soils is optimised at soil organic carbon levels of 2% (Fisher *et al.*, 2007). This is achieved by retaining and incorporating stubbles (Kirkby and Fattore, 2006), minimising tillage, and maintaining these practices over the long term (a one-off input from a green/brown manure crop is not long lasting).

Current practices are not conducive to improving soil biological or physical health. These practices include no/limited rotations; cultivation associated with application of Metham sodium; multiple inter-row cultivations to the same depth with tines that create a hard-pan; discing and flattening of beds (as occurred at all red loam sites in May 2020: **Error! Reference source not found.**); and bare fallows. All these practices preclude structure building in red loams as they cause organic carbon to be lost and they disrupt aggregates and destroy soil binding agents. Alternative practices should be investigated to find better, more profitable rotations and cultivation options.

Improving aggregate stability will not necessarily lead to higher yields because of better subbing and water holding. It will, however, improve pore size distribution, which may lessen the impact of waterlogging and make water management easier.

Conclusions

The goal of this investigation was to gain a better understanding of the key factors currently limiting yields of processing tomatoes in the Australian industry. Four main factors were identified in the nine sites that were monitored over the 2019-20 cropping season:

1. Harvest losses
2. Disease
3. Water management
4. Soil type

The perception by the industry that soil constraints are a key limiting factor to achieving higher yields, or the cause of progressive yield decline under continuous tomato production on drip tape, is not generally supported by the observations made in the course of this study. Causal links between previously investigated soil issues and yields were not found at the sites investigated. Despite a strong correlation between yields and aluminium, low pH was not considered a yield limiting factor because the pH of the soil solution during the irrigation season is determined by fertigation and was found to be neutral in-crop. Neither was there strong evidence of widespread compaction, or of consolidation of soil around drip lines affecting flows in older systems.

Lower yields came from smaller canopies and smaller canopies had higher temperatures. Whilst there are problems with using canopy temperature in tomatoes because of the lack of connection between the canopy and the air above it, these higher temperatures did indicate plant stress. However, canopy temperature was influenced by both water stress and disease but not waterlogging, so soil matric potential was a better indicator of waterlogging and water deficit. Using published matric potential thresholds, a strong linear relationship (R^2 = 81%) was found between the yields from eight of the nine monitor sites and the number of days that crops were either waterlogged or water stressed in January and February.

The key soil issue identified was not any one thing *per se*, but rather an interaction between soil type and irrigation. Apart from one grey clay site affected by disease, canopy growth and size at the red loam sites was lower than at the grey clay sites. Differences between the two soil types in the concentration of soluble salts (EC and nitrate) in the surface soil in December showed less water was moving both upwards and laterally in the red loams than in the grey clays. It is postulated that this is the major cause of lower yields in the red loams.

There was no difference in the dry bulk density of the two soil types, yet the variability in the saturated hydraulic conductivity of the red loams was double that of the grey clays. It is concluded large cracks dominate flows in the red loams, with mainly fine pores within peds, as compared to a more uniform pore size distribution in the grey clays. This has two effects:

1. A smaller component of total water and fertiliser flows move upward and laterally in red loams compared to in grey clays, so the wetted volume of soil is smaller;
2. Flows are concentrated in macropores (cracks) in red loams compared to a more uniform distribution of flows in grey clays, so the red loams ‘fill’ and ‘drain’ more quickly than the grey clays.

If deep drainage was higher in these soils because of their lighter texture and/or preferential flow, then less fertiliser and water would have been available to the crops growing in them.

These factors mean that irrigation system design and management for these two soil types should be different. Simulation modelling to determine optimal emitter rates, spacings, and depths in red loams is needed to better match systems to this soil type. Irrigation scheduling tools, such as matric potential sensors and IrriSAT, should also be adopted to refine irrigation management and reduce the incidence of waterlogging and water stress. Soil solution sampling should also be undertaken to determine water and fertiliser losses below the root zone and inform irrigation and fertiliser management to improve efficiencies.

Improving the structure of red loam soils to increase aggregate stability and create a more uniform pore size distribution would assist and complement efforts to improve irrigation and fertiliser management. Because structure in red loam soils is primarily determined by organic matter, changes to current practices will be required if this is to be achieved. Investigation of new or alternative rotations and cultivation options are needed to address this issue.

Recommendations

1. Establish a monitoring program to track progress towards targets

As well as being specific, goals should be realistic and achievable, progress should be measurable, and there should be a time frame for achievement.

Determine the theoretical physiological potential yield for tomatoes in the Murray valley based on radiation and temperature and assess inter-seasonal variation to set a realistic benchmark yield that is achievable in most years.

Establish a monitoring program to track progress towards this target and identify successful and unsuccessful actions and make changes where necessary.

The monitoring program should identify improvements in major yield limiting factors:

1. Harvest losses
2. Disease
3. Water and fertiliser efficiency

Put a time frame on achievement of this target by the industry.

2. Use plant monitoring to link soil treatments to their effect on crops

There has been a history of studies measuring various soil parameters and attributing adverse numbers to low yields without demonstrating a causal link.

Soil research projects should include the measurement of plant responses to applied treatments, as well as yield, in their proposed methodologies.

NDVI from IrriSAT is an easy and cost-effective means for tracking canopy growth.

Canopy temperature, if measured alongside NDVI and soil matric potential, has potential for assessing crop stress in real-time, differentiating disease from water stress, and determining effects on canopy growth. However, further work is required to develop a suitable temperature reference surface.

4. Investigate more profitable rotation and cultivation practices that improve aggregate stability in red loam soils

Greater aggregate stability in red loam soils may improve their water holding and reduce the incidence of waterlogging and water stress. However, aggregate stability in these soils depends on soil carbon and current practices don't allow this to be improved.

Investigate ways of increasing soil carbon levels in red loam soils through:

1. **more profitable rotations that improve structure and lessen disease risk.**
2. **conservation tillage.**

3. Improve irrigation design and management for red loam soils

Improvements in irrigation system design and management are needed to reduce the incidence of waterlogging and water stress, and to potentially improve water and fertiliser efficiencies in red loam soils.

Use simulation modelling to:

1. **determine optimal emitter rates, spacings and depths for red loam soils.**
2. **simulate the fate of nutrients in red loam soils to investigate whether changes to fertigation and water management can improve water and fertiliser efficiencies.**

This work should be supported by the collection of soil solution samples below the root zone to ascertain the magnitude of water and fertiliser losses through deep drainage.

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