A Review of Subsurface Drip Irrigation in Vegetable Production

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Executive Summary

The irrigation industry is under pressure to improve water use efficiency and reduce environmental impacts. In the Sydney region, drip irrigation is not widely used for vegetable production, although it has the potential to improve irrigation performance. From this review, it can be concluded that sub-surface drip irrigation (SDI) might improve water use efficiency, and reduce environmental impact more than surface drip. There would be large benefit for vegetable producers in the Sydney region. It may also overcome two important objections to drip irrigation, the high ongoing cost and the disruption to normal cultural practices.

However, crop establishment with SDI was identified as a specific issue due to poor or uneven surface wetting. Increased irrigation frequency and irrigation amount may improve surface wetting, although in practice, SDI can increase drainage during the establishment period, which appears to be related to the increased irrigation amount. Shallow tape placement is also helpful, but this has practical limitations due to farm cultural practices.

A promising innovation is the inclusion of a narrow impermeable plastic barrier below the drip line and geotextile layer above the drip line, designed to improve surface wetting. The most recent version of this product has not been evaluated for its effects on surface wetting and crop establishment. Thus there is a need to test whether surface wetting is improved, and also whether this leads to improved establishment. I hope that this review would invoke greater interest in SDI for those who read this document.

This paper is part of the Masters research project titled 'Improved lettuce establishment by subsurface drip irrigation'. A complete copy of the thesis and other related publications can be obtained from www.irrigationfutures.org.au
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1. Introduction

Irrigation in the Australian vegetable industry has traditionally been dominated by the use of surface irrigation. However, increasing pressures on water availability, the potential yield increase through improved control of soil and plant water relationships, and the benefits of reduced labour, fertilizer and pesticide cost, have raised vegetable grower interest in alternative irrigation application techniques, including drip irrigation systems.

Drip irrigation has the potential to use scarce water resources most efficiently to produce vegetables (Locascio, 2005). The modern development of drip irrigation started in Great Britain during World War II and continued in Israel and other countries (Camp, 1998). The major benefits of drip irrigation are the ability to apply low volumes of water to plant roots, reduce evaporation losses, and improve irrigation uniformity (Schwankl, et al., 1996).

Subsurface drip irrigation (SDI) applies water below the soil surface, using buried drip tapes (ASAE, 2001). It has many benefits over conventional drip irrigation (Singh and Rajput, 2007). The biophysical advantages are the lower canopy humidity and fewer diseases and weeds (Camp and Lamm, 2003). The yield and quality of vegetable crops can improve with a buried drip system compared with a surface drip system (Sammis, 1980; Phene et al., 1987; Bar-Yosef, 1989). Environmental benefits include the ability to manage nutrient and pesticide leaching and the threat to groundwater (eg Lamm, 2002). However, SDI is not without problems (Lamm, 2002; Harris, 2005b; Lamm and Camp, 2007).

This review provides context for the vegetable production industry in Australia, with a particular focus on issues for production in the Sydney region (Section 2). Drip irrigation design and management and its adaptation to SDI are reviewed in Section 3, including identification of problems with SDI. These are related to soil factors in Section 4, leading then to Conclusions relevant to the review reported here.
2. Vegetable production in Australia

Vegetable production in Australia is dominated by Queensland, New South Wales and Victoria, where more than 4,000 farms produce vegetables for sale (ABS, 2005). The largest area is in Queensland. Over the four years (2000-2004), the number of farms fell by 19 %, but the industry continued to be dominated by small farms. The value of output from the typical vegetable farm rose from $281,000 in 2000-2001 to $387,000 in 2003-2004. Fifty years ago, the average Australian consumed around 130 kg of vegetables annually. Today, per capita consumption is 162 kg. If vegetable consumption increases at the same rate, the per capita consumption should reach around 188 kg by 2050 (AUSVEG, 2004). Consumer demand for vegetables is rising over the long-range, so there is need for continued expansion in vegetable production.

Most vegetable farming is characterised by intensive management including irrigation. A major problem faced by farmers is the cost of and access to water (Hickey et al., 2006). However, improvements in the productivity of irrigation water are being made. For example, the average return from vegetable production per ML rose from $1,762/ML in 1996/97 to $3,207/ML in 2000/01 (ABS, 2002). An industry report attributes this to increased use of water-efficient delivery systems such as drip irrigation, irrigation scheduling and soil moisture monitoring, which help achieve a good quality product resulting in higher prices in the market (Hickey, 2005).

2.1. The NSW and Sydney Basin industry

New South Wales’s vegetable production districts are the Sunraysia, Riverina – MIA (Murray Irrigation Area), Slopes and Tablelands and Sydney Basin (McMullen, 2000). The Sydney Basin including Greater Western Sydney, the focus of this review, supplies the full range of fresh vegetables to the local market. The vegetable industry in NSW contributes approximately $300 million to the economy. Nearly 26 % of the total value of this industry is produced by the Sydney Basin, where the major vegetable crops are lettuce (*Lactuca sativa* L.), cabbage (*Brassica oleracea* var. *Capitata*), and cauliflower (*Brassica oleracea* var. *Botrytis*) (Hickey and Hoogers, 2006). Most ‘Asian vegetables’ in NSW are produced on 340 small farms of about 5-20 acres in Western Sydney, equally contributed by Chinese, Cambodian and Vietnamese growers (Nguyen, 2000).

Lettuce is a common salad vegetable in Australia. Several types of lettuce are available: crisphead, butterhead, romaine (cos) and leaf varieties (Tony, 2004). Lettuce has a short growing season, commonly reaching maturity in about 6 to 10 weeks from sowing, depending upon the type. All commercial lettuce production is uses ‘transplants’ or nursery-raised seedlings. They require less time in the field (Kinsela,
allowing more intensive cropping. They also overcome establishment problems and the cost of thinning (Tony, 2004).

FAO (2000) defined the area of farm units surrounding towns as ‘peri-urban’, supplying fresh vegetables, fruit. In all countries, rural to urban migration is placing pressure on the peri-urban area where housing and industrial development interact with food production (Brook and Davila, 2000). Sydney’s peri-urban zone is characterised by an inner zone of market gardens, an intermediate zone of poultry-horticulture and an outer zone of dairy or mixed farming (Johnson et al., 1998).

According to the Agricultural Land Classification System, the Western Sydney Peri-Urban Horticultural region is arable land Class1 (Hulme et al., 2002) with high to very high productivity.

2.2. Irrigation water sources and issues arising

Many peri-urban vegetable growers in the Sydney region use potable water from the Sydney water supply as their main water source (Dang, 2004), although there is also a significant industry based on irrigation from the Hawkesbury-Nepean River and its major tributary (South Creek) as well as farm dams. Out of 3,000 irrigators, approximately 1,500 are river pumpers, 750 draw from farm dams and the remaining 750 irrigators, mainly vegetable growers, use town water (Hickey et al., 2006).

Charges for town water used by vegetable growers are based on the commercial Tier 1 rate of $1.20/kilolitre from October 2005. Peri-urban vegetable growers pay annually ~A$10,000 to A$20,000 for water (Hickey et al., 2006). They are also affected by water restrictions during periods when water levels in the Sydney Water Reservoirs are low (Sydney Water, 2007), and will compete increasingly with urban and industrial users (Maheshwari and Simmons, 2003).

Farmers in this area practise intensive horticulture. Irrigation is excessive and not uniform, because overhead sprinklers are most common, and mostly farmers do not use any form of irrigation scheduling or soil water monitoring (Senn, 2001; Maheshwari et al., 2003). Drip irrigation is rarely used in the Sydney region, apparently because surface drip systems are seen as costly, they are said to interfere with normal cultural practices, and there are no guidelines for designing and managing drip systems across the diverse soils and climates of the Sydney region (Cornish et al., 2005). Excessive irrigation on the farms investigated by Cornish and Hollinger (2002) was associated with high stormwater runoff and nutrient loss from farms, although the magnitude of loss depended on soil type (Hollinger et al., 2001). In two on-farm trials, Hollinger et al. (2001) found that SDI greatly reduced irrigation requirement. It also reduced
stormwater runoff because the soil profile was generally drier and accepted more rainfall before runoff occurred.

Subsurface drip irrigation could overcome two main objections to surface drip irrigation. One is the high cost associated with frequent removal and replacement, provided the SDI system lasts long enough to offset the high initial set-up cost. The other is interference with cultural practices. Reduced tillage based on semi-permanent beds (Senn and Cornish, 2000) requires only shallow cultivation, potentially allowing SDI tube to remain undisturbed for many years, without impeding cultural practices.

These findings demonstrate the significant need in the Sydney region to improve irrigation efficiency and help address the pressures of increasing cost of water and restrictions on supply. Given the irrigation systems and management practices currently being used, there is scope to meet this need with drip or particularly subsurface drip irrigation, although installation and management will need to be adapted to the range of soils and the seasonally varying climate of the region.
3. Drip irrigation and its adaptation in sub-surface drip irrigation management

Drip irrigation systems allow water to be applied uniformly and slowly at the plant location so that essentially all the water is placed in the root zone (Johnson et al., 1991).

Drip systems are categorised according to their placement in the field:

- Surface drip irrigation: Water is applied directly to the soil surface.

- Subsurface drip irrigation: Water is applied to below the soil surface through perforated pipes.

Subsurface drip irrigation has been used in Australia and elsewhere for crops including citrus, cotton, sugarcane, some vegetables, sweet corn, ornamentals, lucerne and potato (Raine et al., 2000; Alejandro and Eduardo, 2001; Thorburn et al., 2003; Bhattari et al., 2004; Shock et al., 2004; Lamm and Trooien, 2005). Subsurface drip has proven to be an efficient irrigation method with potential advantages of high water use efficiency, fewer weed and disease problems, less soil erosion, efficient fertilizer application, maintenance of dry areas for tractor movement at any time, flexibility in design, and lower labour costs than in a conventional drip irrigation system. However, there are also potential disadvantages with SDI, which mainly relate to poor or uneven surface wetting and risky crop establishment (Camp et al., 2000; Lamm, 2002; Raine and Foley, 2001).

3.1. Design and installation

Subsurface drip irrigation systems comprise of a filter leading to the main supply tube, sub-main, laterals that convey water to the emitters (Harris, 2005c).

3.1.1. Lateral drip line

Tapes and tubes are available for use as laterals. Tape products are thinner than tubes (Neufeld et al., 1993). Commonly, tube wall thickness ranges from 0.4 mm to 1.5 mm (Hanson et al., 2000). Camp et al. (2000) identified two classes of tape wall thickness. Flexible thin-walled (0.15 mm to 0.30 mm) tapes are typically used for shallow installation, whilst thicker-walled (0.38 mm to 0.50 mm) tapes are installed deeper or where the soil does not provide sufficient support to prevent collapse by equipment or soil weight. O’Neill et al. (2002) used 0.38 mm thickness of tape for potato (Solanum tuberosum L.), corn (Zea mays L.), alfalfa (Medicago sativa) and pinto bean (Phaseolus vulgaris L.) production in sandy loam soils. Successful production of
lucerne with sub surface drip irrigation was recorded by Thompson (2005) in Victoria, using 0.38 mm tape.

3.1.2. Tape installation depth

The use of surface versus subsurface drip irrigation varies by region and by crop, and is often based on perceived constraints on the vertical placement of the drip tape/tube or laterals (Clark and Smajstrla, 1996). With SDI, the choice of drip tape depth is influenced by crop, soil, climate characteristics and anticipated cultural practices, but it generally ranges from 0.02 to 0.7 m (Camp, 1998). It is often in the range of 0.05 to 0.2 m for shallow rooted horticultural crops. From the literature, a depth of 0.15 m for lettuce would be appropriate on the sandy soils at UWS.

Although installation depth is generally decided for horticultural reasons, another consideration for determining depth is that deeper placement (0.45 m) will be required if the primary aim is to reduce soil evaporation and capture the potential benefit of improved water use efficiency (yield and quality) that is possible with SDI (Bryla et al., 2003).

With the shallow systems, relatively deeper installation should reduce soil evaporation and also allow for a wider range of cultural practices. However, as noted above, deeper installation may limit the effectiveness of the SDI system for seed germination/crop establishment. Deeply placed drip lines may require an excessive amount of irrigation for germination/crop establishment. This practice can result in off-site environmental effects (Camp, 1998), and it reduces water-use efficiency. Deeper placement may restrict the availability of surface applied nutrients and other chemicals (Camp and Lamm, 2003).

Relatively shallow tape placement has been tried for many years to assist germination (Burt and Styles, 1994). Recent example includes corn on a silt loam (Lamm and Trooien, 2005). Germination of tomato (Lycopersicon esculentum Mill.) under SDI was better with drip line depths of 0.15 and 0.23 m than at 0.3 m on clay loam soil (Schwankl et al., 1990). It can be assumed that shallow placement is especially important for establishment if there is no supplementary source of surface irrigation.

Shallow placement of drip tape is generally required also for satisfactory growth of shallow rooted crops in sandy soils, which have limited capillary water movement (Broner and Alam, 1996); although this is not always the case, as Rubeiz et al., (1989) found higher zucchini (Cucurbita pepo) yield at 0.15 m depth than 0.04 m depth on a coarse loam soil.
In Australia, tape depth of 0.25 to 0.30 m is used in the Queensland cotton (Gossypium spp.) industry on cracking clay soils (Raine et al., 2000). There are regional differences in the tape placement, with growers in NSW generally installing more deeply than in Queensland (Raine et al., 2000).

3.1.3. Lateral spacing

An overview of published studies shows that lateral spacing ranges from 0.25 to 5 m for SDI, as determined by crop behaviour, cultural practices soil and properties. Wider lateral spacing is practiced in heavy textured soil (Camp, 1998). Closer spacing is recommended for sandy soil (Phene and Sanders, 1976). Lateral spacing is generally one drip line per row/bed or an alternative row/bed with one drip line per bed or between two rows (Lamm and Camp, 2007). With row crops such as tomatoes, laterals are often spaced 1-2 m apart. Lateral spacing of 1.5 m in sub-surface drip-irrigated corn was successful in a silt loam soil (Darusman et al., 1997). Lateral placement of 0.3 m is recommended for subsurface systems in the loamy sand soil of South Carolina for vegetable crops; cowpea (Vigna unguiculata), green bean (Phaseolus vulgaris), yellow squash (Cucurbita pepo), muskmelon (Cucumis melo) and broccoli (Brassica oleracea) (Camp et al., 1993). Lateral spacing of 2 m intervals on a 1:2 drip tape:crop row has been successful in Queensland for cotton (Raine et al., 2000).

3.1.4. Installation

Lateral lines should be laid following the contour of the land as closely as practicable to avoid pressure variations within the line due to elevation change (Haman and Smajstrla, 2003). The first step in installing a successful SDI system is maintaining proper hydraulic design. This allows the system to deal with constraints related to soil characteristics, field size, shape, topography, and water supply.

Lateral diameter and length influence water application uniformity (Kang et al., 1999). Lamont et al. (2002) observed in vegetables in the USA that a tape diameter of 125–200 mm was the industry standard and common for subsurface drip irrigation where rows range from 90 m to180 m. In Greece, 17 mm polyethylene pipe was used at the shorter row length of 30 m for sugar beet (Beta vulgaris L.) research using subsurface drip (Sakellariou-Makrantonaki et al., 2002).

3.1.5. Emitters

Emitters are plastic devices which precisely deliver small amounts of water. Hla and Scherer (2003) described two types of emitter. Point-source emitters discharge water from individual or multiple outlets. Line-source emitters have perforations, holes, porous walls, or emitters extruded into the plastic lateral lines (Ayars, et al., 2007).
Line-source emitters are generally used for widely spaced crops such as vines, ornamentals, shrubs and trees. Point source emitters are used for small fruits, vegetables and closely spaced row crops (Bucks and Davis, 1986). The emitters used for SDI are much the same as those used for surface drip, but the emitter is fixed internally in the drip line (Harris, 2005c).

3.1.6. Emitter spacing

Soil characteristics and plant spacing determine emitter spacing. Spacings used in Queensland are mostly between 0.3 m and 0.75 m for row crops (Harris, 2005d). Kamara et al. (1991) used 0.3 m emitter spacing for drip-irrigated cotton grown in sandy loam soil in the USA. Similarly, an emitter spacing of 0.3 m was suitable for corn production for deep silt loam soils under subsurface drip (Lamm and Aiken, 2005). In a semi-arid environment, 0.45 m emitter spacing was used in clay loam soils for drip-irrigated corn (Howell et al., 1995). In general, emitter spacing should normally be less than the drip lateral spacing and closely related to crop plant spacing (Lamm and Camp, 2007).

3.2. Flushing capacity

A critical area of design that impacts on system performance is the flushing capacity. Many SDI systems appear to have been installed with inadequate flushing capacity, resulting in sediment deposition, decreases in flow volumes and blockages (Pitts et al., 1996). This will produce higher backpressures in the mains, which may also affect system performance (Lamm and Camp, 2007). Retrofitting large valves or increasing the number of valves may solve some flushing problems (Raine et al., 2000).

3.3. Water application uniformity

Water application uniformity in microirrigation depends on system uniformity and spatial uniformity in the field (Wu et al., 2007).

3.3.1. System uniformity

The system uniformity is affected by system design factors such as lateral diameter and emitter spacing (Wu et al., 1986), and manufacturing variation (Bralts et al., 1981a). It is also considered to include emitter clogging (Bralts et al., 1981b). The parameters used to evaluate microirrigation system application uniformity are: the Uniformity Coefficient (UC); emitter flow variation \( q_{\text{var}} \); and Coefficient of Variation \( \text{CV} \) of emitter flow (Bralts and Kensar, 1983; Wu et al., 1986). Using these parameters, Ayars et al. (1999) discussed various drip tape products and determined the values of these uniformity parameters. System uniformity values predicted by
design or evaluation models are similar for both surface and subsurface drip (Camp et al., 1997).

3.3.2. Spatial uniformity in the field

The spatial uniformity in the field refers to variation in soil water. In addition to system design factors noted above (Wu et al., 2007), it includes variation due to field topography and soil hydraulic properties (Burt and Styles, 1994; Burt et al., 1997).

3.3.3. Causes and consequences of non-uniformity

The causes of non-uniformity include unequal drainage and unequal application rates (Burt, 2004). Even where system uniformity is high, variation in soil properties, such as hydraulic conductivity, can affect drainage and lead to variation in water content. Application uniformity may be directly related to yield (Solomon, 1984b; Letey, 1985). Non-uniformity in one field (45%) was estimated to be mainly due to pressure differences, with only 1% due to unequal drainage and 2% due to unequal application rate (Burt, 2004). Burt (2004) considered the typical manufacturing coefficient of variation in tube today is only 0.02 to 0.06, which will be negligible. Soil ‘excavating’ by subsurface emitters was shown to increase flow rate by 2.8% to 4%, but not sufficiently to affect uniformity calculations (Sadler et al., 1995).

One consequence of non-uniform application is increased drainage (Ben-Asher and Phene, 1993; Phene and Phene, 1987), assuming irrigation for uniformly good crop growth. Drainage may also occur if the application is uniform but the soil water holding capacity or hydraulic properties are not uniform.

Obtaining sufficiently moist soil for germination and crop establishment by applying uniform irrigation to soils which are inherently variable is a challenging issue for SDI (Patel and Rajput, 2007). They found that to provide adequate irrigation water for potato plants in the early growth period, they had to be over-irrigated, leading to more downward movement of water on sandy loam soil than upward capillary movement of water.

3.3.4. Minimising non-uniformity

Overall, minimising non-uniformity of the drip system requires: a design which considers the topography of the field (Wu et al., 2007) periodic checking of the system (Clark and Phene, 1992), and irrigation scheduling (volume and frequency) (Burt et al., 1997). Greater irrigation uniformity can be achieved by using pressure-compensating emitters in surface and subsurface drip (Schwankl and Hanson, 2007).
Flow meters are widely recommended to check the system performance in sub surface drip irrigation (Alam et al., 2002). They are used to determine the rate and volume of water applied in an automated irrigation control system (Ayars and Phene, 2007).

3.3.5. Comparison of uniformity in surface and subsurface drip

In SDI, emitter clogging and accumulation of salt caused by evaporation is less than in surface drip (Hills et al., 1989a). More uniform water content was observed in the root zone with SDI than surface drip (Ghali and Svehlik, 1988). In an SDI system more uniform water content in root zone was observed than surface drip, and thus drainage would be less with SDI (Ben-Asher and Phene, 1993; Phene and Phene, 1987).

3.4. Management of SDI

3.4.1. Discharge rate and irrigation frequency in relation to crop and soil type

Subsurface drip irrigation systems generally consist of emitters that have discharge rates less than 8 L/hr (ASAE, 2001). A discharge rate of 0.25 L/hr gave high yield of corn in sandy loam soils of Israel (Assouline, 2002), although the difference in yields between discharge rates was not statistically significant. In a silt loam soil a discharge rate of 0.5 L/hr gave the highest onion (Allium cepa) yield (Shock et al., 2005). In a drip system, frequency and emitter discharge rate determine the soil water availability and plant water uptake pattern (Coelho and Or, 1996; 1999) and consequently yield (Bucks et al., 1981; El-Gindy and El-Araby, 1996).

Illustrating the importance of matching irrigation frequency to soil type, Ruskin (2005) reported that a coarse textured sandy soil required drip lines with higher flow rates and shorter irrigation cycles than clay soil. Similarly, shallow rooted vegetable crops on fine sandy soils in Florida required frequent (once or more per day) water application (Haman and Smajstrla, 2002). Conversely, in a clay loam soil, drip irrigation applied every second day achieved maximum tomato yield (Dalvi et al., 1999). High frequency irrigation seems to be especially important for coarser-textured soils, high frequency SDI gave best yields of processing tomato in a sandy loam soil (Ayars et al., 1999) and of potato in loamy soils in China (Wang et al., 2006).

High frequency water application under drip enables maintenance of salts at reasonable levels within the rooting zone (Mmolawa and Or, 2000b).

The main reported benefit of increased irrigation frequency with SDI is the increased yield. A less commonly reported benefit of increased irrigation frequency is improved crop establishment (Phene and Beale, 1976). As crop establishment is a common problem in SDI (considered in detail in Section 3.6), it is surprising that there seem to
be relatively few studies of irrigation frequency in relation to establishment. More frequent or pulsing irrigation, which involves applying small increments of water multiple times per day rather than applying large amount for long duration, has been advocated to improve surface and near surface soil moisture wetting for crop establishment (Lamm and Camp, 2007). However, there is a lack of operational guidelines for SDI (Lamm and Camp, 2007). In Australia, a comparison of pulsed and continuous irrigation on a Hanwood loam soil in NSW revealed very little difference between treatments, leading the author to conclude that responses depended on tape depth and soil type (Miller et al., 2000).

Other potential benefits of high frequency SDI are reduced deep drainage of water (Ayars et al., 1999), although for this it will be important to have both uniform application and uniform soil and crop growth. High frequency SDI may have lower water requirement, as shown by Wendt et al. (1977).

The flow rate of the drip line has to match the particular soil type. When soil hydraulic conductivity decreases, the pressure head of the soil next to the emitter will increase, which reduces the flow rate of emitters (Warrick and Shani, 1996). On the other hand, emitter discharge decreases due to backpressure, which depends on the soil type, possible cavities near the dripper outlet, and the drip system hydraulic properties (Shani et al., 1996). When the pressure in the emitter increases this may significantly reduce the source discharge rate (Lazarovitch et al., 2005).

It was noted earlier in this review that soil types on which intensive horticulture is practised in the Sydney basin vary from uniform sandy alluviums to loam overlying heavy, poorly drained clay. This variation presents a challenge to farmers to match discharge rate to soil type and select appropriate irrigation frequencies, especially when a wide range of crops is grown.

Crop type also influences optimum irrigation frequency, even amongst vegetable crops. For example, on loam soil, cantaloupe (Cucumis melo) yield was higher with weekly irrigations compared to daily irrigations, whilst onion yield was higher for daily irrigation compared with weekly irrigation (Bucks et al., 1981).

In most cases, supplementary irrigation has been used in establishment (eg Schwankl et al., 1990; Howell et al., 1997). Of the many papers dealing with irrigation management with SDI, few appear to have independently varied management for the establishment and growth periods other than adjust the crop factor. It appears that crops are often over-watered in the establishment period (Enciso et al., 2007; Patel and
Rajput, 2007) to ensure establishment. This has been reported to increase drainage (Howell et al., 1997)

One topic which appears to have received no study is the need to vary irrigation frequency through the life of a crop to meet different requirements. Frequent irrigation may be needed for good establishment, but frequent irrigation subsequently should reduce deep drainage, and increase water use efficiency. This approach is analogous to securing establishment by increasing irrigation rate above the crop requirement determined by $K_c$ and ET, (Howell and Meron, 2007), but with less risk of increased drainage.

3.4.2. Fertigation via drip irrigation

Whilst this review is not concerned directly with ‘fertigation’, the application of nutrients together with the irrigation water, there are some considerations directly relevant to SDI, so the topic will be briefly reviewed. Fertigation is a sophisticated and efficient method of applying fertilizers with irrigation water (Magen, 1995). It contributes to the achievement of higher yields and better quality by increasing fertilizer efficiency (Haynes, 1985; Imas, 1999), regardless of whether DI or SDI is being used. In addition, minimization of leaching below the root zone may be achieved by fertigation (Hagin and Lowengart, 1996; Hanson, 1996).

Although fertigation can be used with any drip irrigation system, a major potential advantage of subsurface drip is that water and nutrients are potentially used more efficiently when compared to surface installation (Phene et al., 1987). Frequency of fertilizer injection can range from once a week to daily for drip irrigated vegetable crops (Marr, 1993). Combined SDI and nutrient management schemes have been developed for several vegetable crops, including collard, mustard, spinach, and romaine lettuce (Thompson and Doerge, 1995a and b, 1996) and corn (Lamm et al., 2001). Subsurface drip irrigation and fertilizer management together has been found to increase yield on tomato, sweet corn and cantaloupe (Ayars et al., 1999), sweet corn (Bar-Yosef, 1989), cabbage and zucchini (Rubeiz et al., 1989).

Subsurface drip irrigation provides incremental application of nitrogen and water. With good management, this has been reported to reduce NO$_3^-$ leaching and contamination of groundwater in lettuce production (Thompson and Doerge, 1996). For crops such as broccoli, celery and lettuce, N uptake is low in the first half of the season and higher before harvest. Fruiting crops such as tomatoes, pepper and melons require little N until flowering, then increase N uptake, reaching peak uptake during fruit set. These factors need consideration for drip irrigation with fertigation (Hartz, 1996).
Water and fertigation requirements need to be established for each crop, as significant differences occur. For example, watermelon yield may be increased by maximising the interactive effects of water and nitrogen applied through SDI on sandy loam soil (Pier and Doerge, 1995), whereas for broccoli production with SDI on sandy loam soils, fertigation frequency had no effect on yield (Thompson et al., 2002).

Vazquez et al. (2005) observed substantial drainage during the crop establishment period of processing tomato under drip irrigation, when the roots explore only a small volume of soil and water absorption capacity is small (Jackson and Bloom, 1990). The excessive irrigation and associated drainage of tomatoes during establishment caused large N losses (Vazquez et al., 2006). So, if extra irrigation is required to ensure establishment and this creates a risk of drainage, the fertigation regime needs to be varied to minimise the risk of N leaching.

SDI may also manage the placement and availability of immobile nutrients (eg. P). The restricted mobility of the phosphate ion implies that pre-irrigation mixing of P in both clay and sandy soils is necessary, supplemented by addition to the irrigation solution, to obtain a uniform P concentration in the soil volume (Bar-Yosef and Sheikholeslami, 1976). Immobile nutrients are delivered at the centre of the soil root volume rather than on top of the soil in subsurface drip (Martinez et al., 1991). Fertigation with P in SDI has improved yield, root growth and environmental performance in tomato (Ayars et al., 1999) and sweet corn (Phene et al., 1991).

Potassium is also easily soluble in water and applied through drip irrigation. Phene and Beale, (1976) have shown that daily low rate application of nitrogen and potassium with a high frequency drip irrigation system improved nutrient uptake efficiency of sweet corn in sandy soils and reduced leaching loss.

3.5. Growth and yield of vegetables in surface and sub surface drip irrigation

As a general guide, crops which are suitable for surface drip irrigation are also suited to SDI (Lamm and Camp, 2007). With good agronomic practices, increased yields have been reported for a wide range of crops. These include lettuce (Hanson et al., 1997); sugarbeet (Sharmasarkar et al., 2001; Sakellariou-Makrantonaki et al., 2002); soluble solid content in transplanted muskmelon (Cucumis melo L.) (Hartz, 1997); onion (Hanson and May, 2004; Shock et al., 2004); and green bean (Phaseolus vulgaris L.) (Metin-Sezen et al., 2005).

The crop response to SDI differs with crop growth characteristics and rooting pattern (Lamm and Camp, 2007). In lettuce, little yield difference was found between SDI and
furrow irrigation in a sandy loam soil (Hanson et al., 1997). Potato yield was increased 27% with SDI over sprinkler irrigation, while reducing irrigation needs by 29%, provided there were drip lines in each crop row (DeTar et al., 1996). SDI had greater yield and higher water use efficiency than surface drip, furrow and sprinkler irrigation with cantaloupe, zucchini and oranges when irrigation was close to consumptive use (Davis and Pugh, 1974).

Information on root distribution is useful to understand crop responses to irrigation and fertigation, especially with the limited wetted soil volume that develops under subsurface drip (Phene et al., 1991). Phene and Beale (1976) showed that root length and rooted soil volume of sweet corn could be improved by frequent irrigation with shallow SDI. They revealed that frequent irrigation maintained a portion of the root zone within the optimal matric potential range. In high-frequency irrigated corn, root length density and water uptake patterns are determined primarily by the soil water distribution under the drippers, whether the drippers are placed on, or beneath the crop row (Coelho and Or, 1999). Most of the root system is concentrated in the top 40 cm of the soil profile in drip irrigated processing tomatoes (Machado and Oliveira, 2003).

Unfavourable results obtained with drip irrigation have often resulted from inadequate root growth and distribution (Brown and Don Scott, 1984), especially in heavy textured soil (Meek et al., 1983). Supply of aerated water with subsurface drip system can maintain aeration of the root zone in heavy clay soils and significantly increase yield of vegetable soyabean and zucchini (Bhattarai et al., 2004).

Subsurface drip irrigation can minimise the period between crops, especially with reduced tillage, and facilitate more intensive cropping. Multiple cropping with SDI has several practical advantages. The subsurface system does not require staking of the drip tubing during initial plant development, does not interfere with machine or manual thinning, weeding, spraying and harvesting of crops as does surface drip irrigation of vegetable crops (Bucks et al., 1981). A continuous cropping system of head lettuce and cabbage by using no tillage could be a potential advantage with subsurface drip (Chase, 1985). Minimal tillage on semi-permanent beds has been widely adopted in the Sydney region, although not with SDI (Senn and Cornish, 2000).

Multiple cropping of vegetables such as cowpea, green bean, squash, and muskmelon in the spring season and broccoli in the autumn season were possible without yield reduction in a humid area (Camp et al., 1993).
3.6. Problems encountered with SDI

There are potential disadvantages with SDI, including high initial investment cost, clogging of emitters by various means, ‘tunnelling’ of soil, and difficulties with uneven wetting and poor plant establishment (Mizyed and Kruse, 1989; Lamont et al., 2002; Charlesworth, 2005). Qassim (2003) and Harris (2005b) discussed the specific benefits and disadvantages of SDI in Australia:

(1) **Crop establishment**: In the absence of supplementary irrigation, germination and crop establishment with subsurface drip irrigation depends on unsaturated water movement (i.e. upwards or laterally from the buried emitter). Therefore, important determinants of uniform germination/establishment include the distance from the emitter to the seed/transplant, soil properties (structure, texture, hydraulic conductivity) and preceding water content (Charlesworth and Muirhead, 2003).

(2) **Soil and water interaction**: According to Lamm (2002), emitter discharge rate can exceed the ability of some soils to distribute the water in the soil. The water pressure in the region around the outside of the emitter may exceed atmospheric pressure thus altering emitter flow. This leads to the “tunnelling” of emitter flow to the soil surface causing undesirable wetting spots in the field. Small soil particles may be carried with the water, causing a ‘chimney effect’ that leads a preferential flow path. The ‘chimney’ may be difficult to permanently remove.

The rest of this section deals with the establishment issue, especially in relation to wetting pattern, which varies with soil type (Brouwer et al., 1990). This is a particular issue for developing SDI for the Sydney Basin because of the wide variation in soil types. Where soil types vary greatly between farms it is both costly and challenging to undertake the research and develop extension recommendations for irrigation design and management that are clear and unambiguous. In fields with heterogeneous soils there can be uneven wetting with its inherent problems.

It was shown earlier in this review that subsurface drip is commonly placed relatively deeply in the soil, even for shallow-rooted horticultural crops, to reduce soil evaporation or to facilitate tillage operations. Consequently, the variable wetting pattern and inadequate surface wetting of subsurface drip irrigation often provides insufficient surface soil moisture to meet the demands of seeds (eg Zimmer et al., 1988) or seedlings.

Several reviews have concluded that crop establishment can be difficult with SDI (Camp et al., 2000; Lamm, 2002; Raine and Foley, 2001), at least for germination of shallow-planted seeds. Harris (2005b) went so far as to say that, in most situations, a
crop cannot be established using subsurface drip irrigation alone. If so, then requiring a parallel surface system represents an added cost to SDI, whilst it would also reduce water use efficiency during the period of surface irrigation, and increase the risk of deep drainage.

For cotton, germination remains one of the greatest challenges for subsurface drip irrigation (Raine and Foley, 2001), although the problem extends beyond germination to include the whole establishment period, including establishment from transplanted seedlings. Problems arising from the poor wetting pattern may persist through the growth period of a crop, unless efforts are made to control the wetting pattern and match it to the crop root zone (Bar-Yosef, 1989).

As discussed previously, wetting patterns can be managed by varying dripper discharge rate and spacing (Lubana and Narda, 2001), influencing the dripper interface (Meshkat et al., 2000), increasing irrigation frequency (Phene and Beale, 1976) or amount (Howell and Meron, 2007), and reducing the depth of installation (Patel and Rajput, 2007). It may also be approached through modifying the SDI tape design (Welsh et al., 1995). Accordingly, research has been undertaken to improve crop establishment under SDI following a range of approaches. However, from the literature discussed previously, none of the solutions involving shallow tape installation or higher discharge rates will be satisfactory under all circumstances.

This leaves modification to the drip tape as the most likely approach to achieve satisfactory performance under a wide range of soil and climatic conditions. Even with this, to achieve adequate surface wetting and remove the risk of poor establishment (Zimmer et al. (1988) under all circumstances, it is likely that situation-specific guidelines will be needed for irrigation rate and frequency. Thus for SDI to be adopted in the Sydney region, and to enhance its adoption elsewhere, further research is needed into modification of the drip tape to improve surface wetting, and into development of appropriate guidelines for irrigation rate and frequency.

The modification in SDI design by adding an impermeable membrane has the potential advantages of changing the wetting pattern (Miller et al., 2000) and inhibiting the downward percolation of water (Welsh et al., 1995). To counter problems of poor germination, a new technique was suggested for manipulating the wetting pattern of SDI using an impermeable membrane to transform the point source of water in drip lines to a broad band source from which a capillary force operates to draw water upward and outward (Welsh et al., 1995). Another new subsoil irrigation system consisted of a V-shaped device which released foil and pipe simultaneously into the soil (Barth, 1999). Although the impervious layer is intended to reduce downward
percolation (Welsh et al., 1995), it is hypothesised here that any benefit may arise because the layer creates a temporary watertable, from which the upward flux of water is increased.

Modifying the drip tape to include the impermeable layer was commercialised in the Capillary Root Zone Irrigation (CRZI) product. It was evaluated in loam and sandy loam soils (Charlesworth and Muirhead, 2003). The results indicated that CRZI provided a more uniform wetting pattern but failed to improve establishment in English spinach. In this case, however, establishment was considered to be good (~50%) with standard subsurface drip because of the particular soil properties that gave rise to adequate surface water. So, despite the improved wetting pattern, germination was no better. The results did show that an impermeable barrier can be beneficial for surface wetting. Similar results have been obtained with lettuce germination (Deery, 2003).

It appears that more research is needed to define the conditions under which the establishment problems arise and to reduce the technical barriers to SDI. Barriers to the adoption of SDI include the need to adapt system design and management to local soil and climatic conditions and constraints.

CRZI has undergone extensive development and is now sold under the trade name Kapillary Irrigation Subsurface System (KISSS™). The advantage of this product over conventional SDI for vegetable seedling establishment has not been evaluated.
4. Soil properties and SDI performance in the vegetable industry

4.1. Role of soil texture and structure

Hanson et al. (1997) compared furrow, drip and subsurface drip irrigation for lettuce on sandy loam soils. There was more sand and less silt under furrow irrigated plots in the top layer of soil (0-0.3 m) due to greater infiltration than drip plots. Sand, silt and clay contents of the 0-0.3 m depth interval were quite constant with distance in subsurface drip. Changes in clay content, cation levels and the pore space around emitters were observed in long term subsurface drip irrigation with processing tomato, rockmelons and onions (Barber et al., 2001). These authors concluded that these changes could have inhibited the movement of water by altering soil hydraulic properties and reducing the spread of the irrigation wetting-front in clay soils. In one study in heavy textured soil in a region where secondary salinity is a problem, subsurface drip irrigation increased the rate of salinization compared with furrow irrigation because of improved structure and reduced slaking and dispersion in subsoil which led to increased solute movement through the soil profile (Hulugalle et al., 2002).

Slaking and dispersion are used to measure the structural stability of soil (Daniells et al., 2002). Gypsum improves soil structural stability and economic use of gypsum depends on soil properties and seasonal condition (Greene and Ford, 1980; Ford et al., 1980). Soil conditioners applied by drip irrigation have also increased water stable aggregation in the wetting zone around the drippers (Shaviv et al., 1987).

Drip irrigation can improve plant water availability in medium and low permeability fine-textured soil, and in highly permeable coarse-textured soil in which water and nutrients move quickly downward from the emitter (Cote et al., 2003). Continuous irrigation at a rate equal to evapotranspiration was optimal for medium textured soils whilst greater application rate was required for coarse textured soils to minimise deep percolation losses (Ghali and Svehilk, 1988). Many experiments have been conducted in both modelling and field research to investigate plant water availability and root uptake pattern in different soil types (Or, 1996; Or and Coelho, 1996; Mmolawa and Or, 2000a and b; Thourban et al., 2003).

4.2. Role of soil hydraulic properties

Knowledge of soil hydraulic properties assists design of irrigation systems (Mehta and Wang, 2004). Non-uniformities in hydraulic properties and infiltration rates are considered to be major reasons for inefficiencies in drip irrigation and may cause non-uniformities in soil water content and could potentially affect plant growth. Soil hydraulic
conductivity is a limiting factor for water uptake by plants under drip irrigation, particularly in sandy soils (Li *et al.*, 2002). However, in clay loam soils, subsurface drip irrigation resulted in very non-uniform soil water contents above the depth of emitters (Amali *et al.*, 1997), which may be corrected by using a membrane under the drip tube.

4.3. Soil chemical responses to drip and sub-surface drip irrigation

For row crops, the drip emitters are often placed at the centre of row beds, below which most salt loading or leaching would probably occur. In one study, soil electrical conductivity, pH and soluble cations were lower under subsurface drip than surface drip (Nightingale, 1985), suggesting increased leaching. Haynes (1990) observed that the conversion of fertigated ammonium sulphate and urea into nitrate-N caused acidification in the wetted soil volume to the surface (0-20 cm) of silt loam soils, also suggesting an increase in leaching. Similarly, acidification throughout the soil profile was observed in vegetable beds in tomato crops (Stork *et al.*, 2003), again suggesting leaching of NO$_3$. This hypothesis finds support in an investigation of commercial production of processing tomato where subsurface drip irrigation, combined with excessive fertilizer application, was thought to cause the leaching of nitrogen (and phosphate) to groundwater depths (Stork *et al.*, 2003). Under drip irrigation of tomato crops on sandy loam soils, Vazquez *et al.* (2005) found that greater drainage occurred during the crop establishment period, which increased the leaching of nitrates previously stored in the soil profile.

From these reports, it seems possible that vegetables crops may be over-irrigated using both subsurface and surface drip. If so, then it may reflect the need to irrigate above crop water requirement in order to maintain acceptable soil moisture in the soil surface, especially in the case of SDI.

4.4. Soil wetting pattern

A basic need for better drip irrigation systems is information about the moisture distribution pattern, shape and volume of soil wetted by an emitter (Levin *et al.*, 1979). The volume of wetted soil represents the amount of water stored in the root zone. Its depth should coincide with rooting depth while its width should be related to the spacing between emitters. One possibility for controlling the wetted volume of a soil is to regulate the emitter discharge rate according to the soil hydraulic properties (Bresler, 1978; Lubana and Narda, 2001).

The wetting front is an important factor in drip infiltration, indicating the boundaries of the wetted soil volume (Bresler, 1978). A simple technique known as the pit method was developed by Battam *et al.* (2003) for design and management of drip systems.
Soil texture is an unreliable predictor of wetting and for adopting different spacing of emitters. For different soil texture, site-specific information on soil wetting is required (Thorburn et al., 2003). Under given climatic conditions, the effect of soil type on the depth-width-discharge combination is influenced by water holding capacity and hydraulic conductivity of the soil (Zur, 1996).

The wetting pattern with SDI can be affected not only by irrigation management, but also SDI design aspects such as emitter spacing and drip line depth. Dripper function can also be modified after installation. In one study, heterogeneity of the soil in the neighbourhood of a subsurface emitter that had been disturbed by farm equipment resulted in low emitter flow, leading the authors to suggest using soil conditioners to improve and stabilize soil structure around the dripper (Shaviv and Sinai, 2004).

The wetting pattern has also been enhanced by the addition of plastic barriers beneath the drip line (Brown et al., 1996; Charlesworth and Muirehead, 2003).
5. Conclusions

The irrigation industry is under pressure to improve water use efficiency and reduce environmental impacts. In the Sydney region, drip irrigation is not widely used for vegetable production, although it has the potential to improve irrigation performance. From this review, it can be concluded that sub-surface drip might improve water use efficiency, and reduce environmental impact more than surface drip. There would be large benefit for vegetable producers in the Sydney region. It may also overcome two important objections to drip irrigation, the high ongoing cost and the disruption to normal cultural practices.

However, SDI may have significant problems with poor or uneven surface wetting, leading to problems with crop germination and establishment. This review and the subsequent research reported in my thesis was undertaken with the broad aim of providing a foundation for the adoption of SDI in the Sydney region, by addressing the problem of risky plant establishment.

Increased irrigation frequency and irrigation amount may improve surface wetting, although in practice, SDI can increase drainage during the establishment period, which appears to be related to the increased irrigation amount. Shallow tape placement is also helpful, but this has practical limitations due to farm cultural practices.

A promising innovation is the inclusion of a narrow impermeable plastic barrier below the drip line and geotextile layer above the drip line, designed to improve surface wetting. The most recent version of this product has not been evaluated for its effects on surface wetting and crop establishment. Thus there is a need to test whether surface wetting is improved, and also whether this leads to improved establishment.

As the impermeable layer adds to the cost of SDI, it is also important to know if the modified tape has any benefit that cannot be achieved by varying irrigation rate or frequency, both of which are known to affect wetting patterns but have received little attention in relation to crop establishment.
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