International innovations in irrigated salad production A brief review of science and industry evidence

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Summary

This report provides a short review of published international literature (both grey and scientific) on the management of irrigation systems for salad production drawing on the latest available scientific and industry evidence.

The review focussed on synthesising information relating to the impacts of different irrigation application methods on yield and water use in salad (lettuce) production, including pressurised overhead irrigation (e.g. sprinklers, centre pivot), localised micro-irrigation (drip or trickle) and gravity fed surface (furrow) irrigation.

The review has shown, not surprisingly, that there is an extensive amount of international scientific literature on irrigation systems in the context of infield performance, and the factors that influence uniformity and efficiency. But the evidence is not crop specific. There is much less UK relevant information available on lettuce crop growth, productivity and the abiotic factors that impact on yield and quality. Most evidence stems from research conducted in the USA. There is a limited amount of information on the combined impacts and relationship between irrigation systems and lettuce productivity, although some papers provide case specific insights.

The industry evidence highlights a growing interest in precision irrigation and variable rate irrigation (VRI), particularly under overhead systems (linear moves and centre pivots) where the application equipment can be modified to apply water variably depending on local spatial variations in soil type, soil moisture availability and crop growth. There has also been major progress over the last few years in the development of 'closed loop' systems that link the irrigation application technology to soil moisture scheduling, driven by rising concerns regarding water availability and energy costs.

This report is intended to support the HDC and its growers in identifying where gaps in knowledge exist in understanding the impacts of irrigation on salad (lettuce) production (yield and quality), what and where international innovations are emerging and where further research effort should be directed.

1 Introduction

1.1 Global production trends

Lettuce (*Lactuca sativa*) is a temperate annual or biennial plant of the aster or sunflower family (*Asteraceae*). The name is derived from the Latin "latucca" which refers to the vegetable's milky juice as it is believed the Romans introduced lettuce into Britain. The first supplies of iceberg lettuce (named because it was packed with ice to survive the long period of transport in warm temperatures) arrived in the UK in the mid-1970s from the USA. But it was not until the 1980's that UK grower's mastered lettuce production. Lettuces are now one of the most important vegetables grown globally, both in terms of economic value and culinary popularity (Coelho *et al*., 2005).

In 2010, the UK was ranked 13th in terms of global salad production (FAO Stat, 2010). China dominates production with 13 million tonnes, representing 53% of world production (Figure 1). The USA is the second largest producer (4 million tonnes) and with China they constitute nearly three quarters (>70%) of production (FAO Stat, 2010).

In China, a large proportion of production is for domestic consumption, making Spain and the USA the major world lettuce exporters (accounting for 36% and 19% of global exports, respectively). The Netherlands, Italy and Belgium each constitute about 10% percent of global lettuce exports (FAOStat, 2010). The UK is ranked 3rd in the world as a net importer of salad after Germany and Canada. In 2010, the UK imported 0.165 million tonnes (equating to 23% more than that which is produced locally) with an estimated value of £ 157 million (FAOStat, 2010).

Since the 1960s, the UK cropped area of lettuces and chicory has fluctuated quite significantly (Figure 2). Production (ha) peaked in the early 1970's at around 10, 000 ha then declined steadily through the 1980s, only to then recover during the 1990's. However, since 1991 the area has dropped by nearly 60% and now stabilized around 6,000 ha, with average productivity of 23 t/ha, down from around 29 t/ha during the 1980s and 1990s.

Figure 1 Major lettuce and chicory producing countries (Source: FAOstat, 2010).

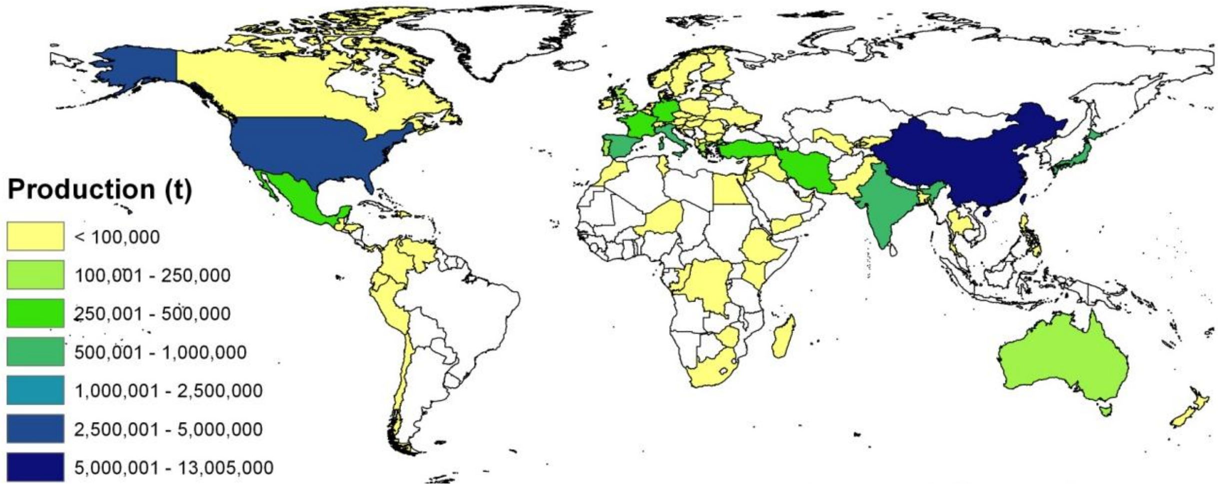
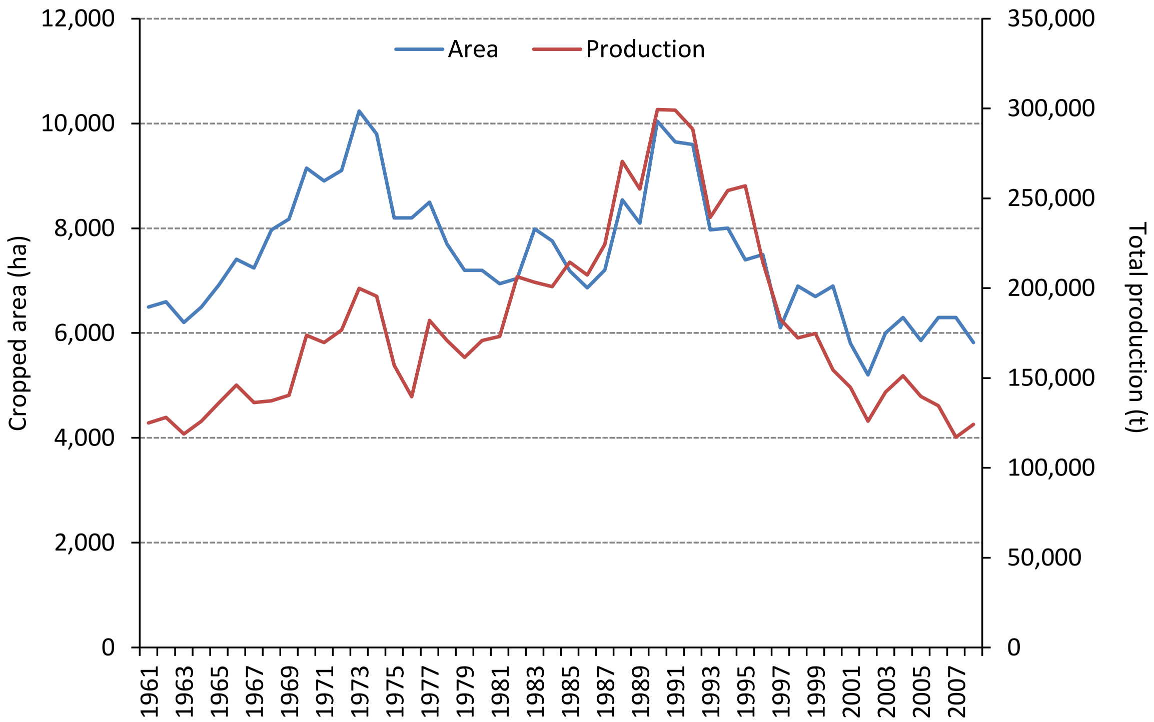


Figure 2 Reported tend in cropped area (ha) and production (t) of lettuce and chicory in the UK between 1960 and 2009 (FAOStat, 2010).



1.2 Lettuce water requirements

Since the harvested part of the crop is the leaf, it is especially important to maintain optimal growth through timely application of both water and nitrogen (Gallardo *et al*., 1996). For lettuce, the critical period is during head development (Norman, 1992). If the plant does not receive adequate rainfall or irrigation during this period, then drought stress can reduce growth by more than all other environmental stresses combined (Perry, 2008).

Lettuce is characterized by a shallow root system (Onken *et al.,* 1979; Exner and Spalding, 1979) so careful management of soil moisture throughout the growing season is critical. Lettuce is grown in a range of contrasting soil types, but best suited to loamy to clay loam textured soils. They also thrive on sandy loams with a high proportion of organic matter or clay textured soils with good drainage. But even relatively short periods of soil moisture stress can adversely affect plant size, leaf area, produce quality and yield (Wahome, 2004). Lettuce thus requires moist soil conditions throughout its growth (Whitaker *et al*., 1974).

The optimal temperature for lettuce growth range from 16 and 20° C. Temperatures below 6° C or higher than 25° C can adversely damage the crop. However, certain varieties have tolerance to lower temperatures especially during early growth stages but near harvest, frost can damage the external leaves and adversely affecting the head and hence storage quality. Conversely, warmer temperatures can increase bitterness and tip-burn (Monaghan *et al*., 2008).

Lettuce yields can reach up to 60 tons/hectare, depending on the local climate, variety, number of growth cycles and soil conditions. In the UK, the crop usually takes between 40 and 80 days to mature. Retailers normally specify a narrow range of acceptable head weights of between 400 to 700 g for an iceberg variety which can then lead to high crop losses in the field during harvest (Harwood *et al.,* 2010)

Due to its shallow rooting characteristics, sensitivity to drought stress and the importance of product quality, most lettuce production is dependent on some form of irrigation, whether full or supplemental. However, the choice of irrigation method is dependent on a number of factors, including water source. For most horticultural irrigation there are concerns specific to the use of wastewater, such as the opportunity for foliar injury, pathogens that may affect the plants and the risk of microbiological pathogens that may affect humans (Tyrrel *et al*., 2009). These latter factors may be of greatest importance (Christen *et al*., 2006).

2 International research evidence

For lettuce production there is no specific irrigation method that is considered ‘best’. All methods have their own distinct advantages and drawbacks. Irrigation systems are typically assessed in terms of their (i) appropriateness and suitability to deliver a uniform and efficient application of water, (ii) their suitability for dealing with water of varying quality, and (iii) their economic viability for a particular crop type, taking into account the costs and benefits of water applied. In recent years, the importance of energy costs and minimising the environmental impacts associated with system performance has also become key drivers for switching technology.

Internationally, the irrigation methods used for lettuce production can be categorised into (i) overhead (e.g. sprinklers, centre pivots, linear moves and booms), (ii) micro (e.g. drip or trickle) or (iii) surface (e.g. furrow) irrigation. Whilst surface irrigation is not practiced in the UK, it is still worth noting its key characteristics as it the most widely used method internationally for irrigating lettuce. A brief description of each of these technologies is provided in terms of their operation and performance. A review of published (scientific) peer reviewed literature is then presented, where possible citing evidence that is specific to managing irrigation for salad production.

2.1 Overhead irrigation

Sprinklers (solid set and hand move)

A solid set system comprises a main line and laterals with either sprinklers or spray nozzles that remain in field throughout the growing season (Figure 3a). Hand move sprinklers consist of a small number of laterals that are moved manually around the field sequentially to cover an irrigation cycle. The capital cost of these systems is much lower than fixed sprinklers but of course labour costs for moving the equipment are correspondingly higher.

Sprinklers are well-suited to irrigating high value horticultural crops which need light but frequent irrigations and can provide ideal germination and establishment conditions for lettuce production. These systems are also suitable for irrigating lettuces on undulating or steep terrain (Figure 3b) although surface run-off can be a problem. In addition to low labour requirements, these systems can be used to limit wind erosion, for frost protection and for applying nutrients or herbicides directly (fertigation) (Mdudzi *et al*., 2010).

Figure 3 Lettuce being irrigated with sprinklers. Photos courtesy of Hans Reinhard (Zefa/Corbis) and Jeff Vanuga (USDA).

The design and management difficulties associated with sprinkler irrigation relate to (i) excessive ponding and run-off due to a mismatch between application rates and soil infiltration rates (mm/hr), and/or (ii) excessive deep percolation due to poor irrigation scheduling and water distribution uniformity. These can be overcome by matching soil conditions to application rates through proper design, system maintenance and good irrigation scheduling practice.

For these reasons, there are a wide range of sprinkler types and nozzle sizes available which allow application rate to be matched with local soil characteristics. On light sandy soils these systems are more suited than furrow, but conversely on soils with very low infiltration rates (<3 mm/hour) special measures may be needed to avoid surface run-off and increase the infiltration rate (Burt *et al*., 1999).

To achieve uniform water application, good knowledge of the sprinkler characteristics and its water distribution pattern are needed. Sprinklers operate within a defined pressure range, whilst the distance between them dictates the volume and application uniformity. Wind distorts the distribution pattern and adversely affects uniformity. However, poor distribution uniformity can also occur on field margins or in odd-shaped corners where the right sprinkler overlapping pattern cannot always be achieved (Christen, 2009).

The sprinkler has undergone significant modification in design and performance over the last four decades. Unit costs have dropped markedly, mainly to plastic construction rather than use of brass components, and solenoid valves, computers and wireless communication all now provide a high degree of management control and flexibility for scheduling. Drawbacks include the high capital investment and operating costs, the risks of foliar damage and fungal disease due to overhead irrigation and the equipment creating obstacles for other in-field farming operations.

Centre pivot and linear move

These systems are used widely in the US, Middle East and Australia where large areas are irrigated. The outer end of a pivot travels much faster than near the pivot, so instantaneous application rates around the field edge are much higher, typically 60–250 mm/hour which is in excess of the infiltration rate of most soils (Heerman and Kohl, 1981). The risk of run-off can be decreased by applying much lighter (smaller), frequent irrigations.

There has also been a trend to modify these systems and fit nozzles to apply water at low energy precision application (LEPA) close to the soil surface (Burt *et al*., 1999). This reduces the application rate, helps preserves surface soil structure and minimises evaporation and wind impacts.

These machines also offer great scope for variable rate irrigation (VRI) and significant progress has been made (notably in the US and Australia) in both hardware and software development for variable control (McCarthy *et al*., 2010) to provide precision irrigation taking into account spatial variabilities in soil type, crop growth and irrigation need.

Travelling hose reels fitted with guns or booms

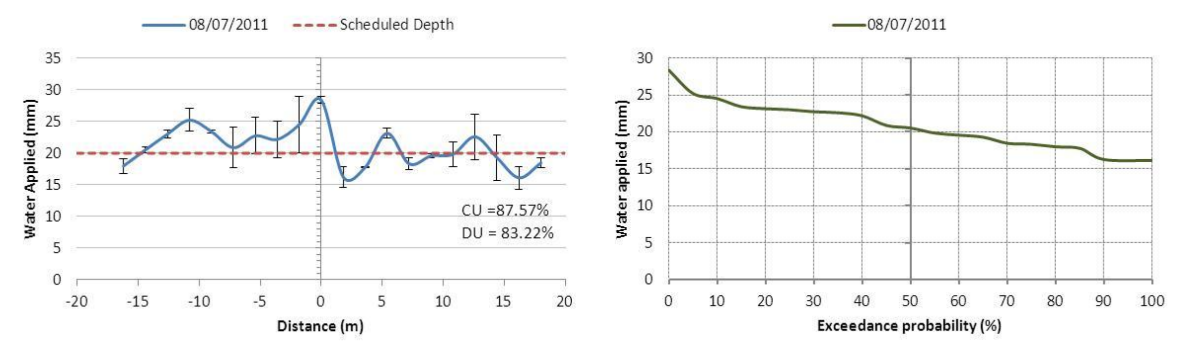
Hose reels fitted with guns are high volume and high pressure systems where the application rate is determined by the raingun (nozzle size), water pressure, machine wind-in speed and lane spacing. The boom has a similar configuration only the gun is replaced with a boom (Figure 4a). Because of the larger droplet size and higher application rates, raingun systems are best suited to light soils with high infiltration rates on crops that can sustain heavy wetting and have good groundcover (pastures, sugar cane, potatoes). They generally have lower uniformity of application especially under windy conditions (Burt *et al*., 1999; Lacey, 2009) compared to other overhead methods. The large droplet size and high application rates mean rainguns are not generally used on lettuces; most growers prefer hose reels fitted with booms to provide irrigation with high uniformity and a smaller range of droplet sizes to limit foliar and soil damage (Figure 4a).

Figure 4 Hosereel fitted with (a) boom and (b) modified with drop tubes on lettuce in Cambridge, UK (2012).

Research evidence

Knox *et al*. (2011, 2012) has shown that hosereels fitted with booms can provide very good levels of irrigation uniformity on lettuces, with coefficients of uniformity (CU) over 85% quite possible (Figure 5a). This is based on transects of catch can data to show the typical variation in irrigation applied depth (mm) along a boom. The test was carried under relatively windy conditions. The average depth of water applied (21 mm) was very close to the scheduled depth (20 mm) giving high adequacy. Figure 5b shows that the average (50% probability of exccedance) depth of water applied was 20 mm whilst the driest (10% probability) and wettest areas (90% probability) received <16mm and >25 mm, respectively. This variation is acceptable and provides useful information in support of developing objective approaches to irrigation scheduling.

Figure 5 Evaluating irrigation system performance of a hosereel fitted with a boom on lettuces in the UK (2011).



On exposed sites windy conditions create drift problems due to the fine spray being carried on the wind. Modifying booms with drop tubes means water is directly onto the soil once the crop develops thus limiting soil splash problems (Figure 4b). For the modified (drag hose) boom the application uniformity (CU) was found to be very high (90-95%) although it is important to recognise that the application depth can be much higher due to the reduced area over which the water is applied. It also eliminates problems associated with irrigating using booms on windy days.

2.2 Localised micro-irrigation

Drip or trickle irrigation aims to minimise the use of water and fertilizer by applying water slowly to the roots, either onto the soil surface (Figure 6) or directly into the root zone (sub-surface irrigation), through a network of valves, pipes, emitters and controllers. Drip irrigation has the greatest potential where water is expensive and/or scarce, where soils are difficult to level and where high value crops are grown (Knox *et al*., 2007; Buck and Nakayama, 1982). Water and energy savings from drip arise from the reduced amount of water pumped. Tiwari *et al*. (1998a, 1998b) reported that drip irrigation is the most effective way to supply water and nutrients to high value horticultural crops including lettuce, saving water and increasing yield and quality.

Figure 6 Drip irrigation on lettuces using softwall tape. Photo courtesy of Access Irrigation.

The main advantages of drip in horticulture are the *potential* water and nutrient savings due to more localized wetting of the crop, since not all the field is irrigated. Small, frequent applications, if appropriately managed, can maintain the plant in optimal water and nutrient conditions with minimum losses via leaching or runoff. These systems are easy to automate with lower labour cost than overhead systems, although the capital (investment) costs are much higher. Applying water directly in the rootzone also has the advantage of limiting the risk of leaf disease and washing out of pesticides from foliage. Walkways and between-row areas remain dry reducing weed growth and provide good field trafficability. As with any system, drip irrigation needs to be well designed, properly installed and carefully managed. Clogging of emitters can be a problem with poor quality water or inadequate filtration. High levels of management and investment make drip irrigation a potentially risky investment for lettuce production.

Research evidence

In Western Australia, McPharlin *et al.* (1995) reported on a comparative study of drip and sprinkler irrigation on lettuce on a sandy. The drip irrigated lettuces showed an increase in marketable yield compared to sprinklers by 19% and 12% for seed-sown and transplants, respectively. An economic analysis revealed that the drip irrigation had increased crop profitability by 21–42%. The nitrogen use efficiency with drip was 25% higher than with sprinkler resulting from better placement and reduced leaching. However, obtaining a uniform germination of lettuce can be a problem with buried drip.

For lettuce, most growers prefer to lay drip tape on the surface to provide frequent watering during the phase of rapid vegetative growth. One drip line is installed between 2 plant rows on 1 m beds, or 3 drip lines installed between 5 or 6 plant rows on a 2 m bed. Drip lines are retrieved before harvest and either reused or disposed. Some growers use drip tape with a wall thickness (>10 mil) which means the tape can be re-used on 8 to 12 crops before it needs to be replaced.

Drip irrigation can limit run-off typically associated with furrow and solid set sprinkler irrigation. It can also be managed to minimize nitrate leaching by fertigating with lower rates of fertilizer and applying less water more frequently than can be achieved using sprinkler or furrow systems.

Research evidence

Monaghan *et al* (2008) reported that drip-based fertigation may improve the application efficiency of water and nutrients while maintaining or improving marketable yield and quality at harvest and post-harvest. Two plantings of lettuce (*Lactuca sativa*) were grown in the UK, with six N treatments and two methods of irrigation and N application. The conventional overhead irrigated treatments had all N applied in the base dressing with irrigation scheduled from SMD calculations. The closed loop treatments had nitrogen and irrigation delivered via drip automatically controlled by a sensor and logger system. The work established that water content in the root zone can be monitored in real time using horizontally oriented soil moisture sensors linked to data logging and telemetry, and that these data can be used to automatically trigger drip irrigation for commercially grown field vegetables. When the closed loop irrigation control was combined with fertigation treatments, lettuce crops were grown with savings of up to 60% and 75% of water and nitrogen respectively, compared to standard UK production systems. However, excess supply of N through fertigation rather than solid fertiliser was more detrimental to marketable yield and post-harvest quality highlighting that care is needed when selecting N rates for fertigation.

But high levels of bicarbonate, manganese, or iron in the irrigation water can create emitter clogging. Periodic injections of acid are used to remove bicarbonate and iron precipitates, but poor filtration does have major impacts on irrigation uniformity.

2.3 Surface irrigation

Surface irrigation is best suited to medium or moderately fine textured soils of relatively high available water holding capacity and conductivities which allow significant water movement in both horizontal and vertical directions. Furrow irrigation systems are characterized by small, evenly spaced, shallow channels installed down or across the slope of the field to be irrigated (Figure 7). The furrow method is particularly suitable for irrigating crops (including lettuce) that are subject to injury if water covers the crown or stem of the plants, as the crop may be planted in beds between furrows and remain dry (Figure 7). With furrow irrigation, it is important not to over saturate the beds, since excess moisture will favour development of bottom rot.

The performance of furrow irrigation is influenced by soil infiltration characteristics which vary across (Walker, 1989; McClymont and Smith, 1996; Emilio *et al*., 1997; Gillies, 2008; Trout, 1990). Furrow irrigation efficiency is further compounded by the furrow-to-furrow inflow variability in both gated pipes and siphon tubes (Trout and Mackey, 1988). In a typical field under furrow irrigation, it is difficult to identify one furrow that is accurately representative of the entire field. Therefore field evaluation of infiltration characteristics based on measurements from a single furrow is unlikely to give an accurate estimation of irrigation performance (Langat *et al*., 2008; Gillies, 2008; Schwankl *et al*., 2000).

Figure 7 Furrow irrigation on lettuces in Arizona (USA). Photos courtesy Jeff Vanuga, USDA (2002).

Khatri and Smith (2006) and Gillies (2008) identified non-uniformity as the major physical constraint in achieving high irrigation performance in furrow-irrigated fields. However, surface irrigation can apply water very uniformly if properly designed and operated (Clemmens and Dedrick 1982). The main techniques to improve distribution uniformity with furrow irrigation include increased furrow flow rate, reduced run length and 'cut-back' flow (Christen, 2010).

Research evidence

Many researchers have investigated the impact of using different irrigation systems on lettuce yield, quality and water consumption. For example, using furrow irrigation, Moore (1970) found that 50% of the applied water was lost to leaching and 20% to runoff with most losses occurring during the early stages (germination and emergence) of lettuce crop development. Hanson *et al.* (1997) compared furrow irrigation with surface and subsurface drip on lettuce yield and the volume of water applied on a farm in the Salinas Valley, California (USA). The overall performance showed similar lettuce yield for the furrow and subsurface drip, but lower yields with the surface drip system. However, greater water use efficiency (WUE) was obtained for the drip irrigation methods, with water applications equivalent to 43–74% of the amount used on the furrow.

A similar study by Sammis and Hanson (1978) reported significant water savings for lettuce with surface and subsurface trickle irrigation compared to furrow and sprinkler irrigation. Robinson (1970) found that using sprinkler irrigation throughout the growing season made it possible to grow lettuces with higher planting density. Comparable lettuce yields and WUEs were observed by Sammis (1980) under sprinkler, trickle and subsurface drip systems. Input costs such as water, fertiliser and cultivation were lower for the drip irrigated crops. Installation of systems such as centre-pivot or drip involves significant capital investment, maintenance and replacement costs (Hickey et al., 2006). However, the benefits achieved from using a pressurized system may not always offset the additional capital and operating costs compared to surface irrigation (Hanson *et al*., 1997; Hutmacher *et al*., 2001).

3 International industry evidence

To complement the international science and research evidence, this section reviews the international industry evidence to identify any 'cutting edge' advances in technologies that may have UK relevance. Further information is provided via hyperlinks to relevant websites (manufacturers, extension services). Following a brief internet and literature survey to identify examples of industry innovation, the findings are summarised below, under three main headings:

1. Technical innovations in irrigation systems (application);
2. Technical advances in soil and crop management (irrigation scheduling);
3. Developments in water resources management (pumping, storage, treatment).

3.1 Technological innovations in irrigation systems (application)

A good summary of recent innovations in irrigation application are available from the 2011 Irrigation Australia conference. Their website has a number of useful downloadable papers and presentations. http://www.irrigation.org.au/index.cfm?/publications/2011-conference-papers

1. Identifying irrigation best management practice through irrigation benchmarking: would you like probes with your drippers? *Maxine Schache, DPI, Victoria.*

   Ten years of irrigation benchmarking of three commodities, namely almonds, dried vine fruit and table grapes, has helped identify on farm irrigation management factors that result in the greatest application efficiencies and returns. This report summarises the statistical analysis of the relationship between crop type, irrigation system, irrigation scheduling method and application efficiency.

2. Piloting IrriSat technology in irrigated cotton. *Janelle Montgomery, NSW Dept Primary Industries, Richard Soppe / Rod Jackson / John Hornbuckle*;

   Following the successful use of the service in horticultural industries, IrriSat SMS was trialled for the first time in irrigated cotton. IrriSat SMS uses satellite imagery to better determine site specific crop coefficients that are needed to calculate crop water use. Customised irrigation scheduling information is sent to irrigators by SMS messaging or via a website on the internet. IrriSat is another option within the 'Scheduling Tool Box.

3. Demonstration of telemetry technology for energy and water use efficiency in irrigation of carrots. *Susan Lambert, Tasmanian Institute of Agricultural Research, Frank Hay, Bill Cotching and Tony Norton*

   A key challenge of vegetable production is to improve water and energy use efficiency. A travelling gun irrigator, common in Tasmanian vegetable production, was retro-fit with telemetry and irrigation components. Preliminary results showed 7.7 t/ha (9%) greater yield of carrots under the modified than the conventional traveller, with 15% and 5% less energy and water. Economic analyses are needed to further quantify benefits.

3.1.1 Precision irrigation (PI) and Variable Rate Irrigation (VRI)

1. In the UK, precision irrigation for onions and lettuces is being developed as part of a Defra Hortlink (HL0196) project under booms and fixed set sprinklers. Field demonstrations will be made during 2013 on selected grower sites. The costs and benefits of precision irrigation in the UK are strongly influenced by summer rainfall which helps to ‘buffer’ the impacts of heterogeneity in irrigation water application. So, ‘poor’ irrigation with low uniformity can be offset to some extent by regular rainfall, although penalties on yield and crop quality can still be significant. Fieldwork and modelling is being used to assess the likely impacts of soil and water variability on final crop yield for onions.

2. A comprehensive review of Australian developments in precision irrigation was completed by R.J. Smith, J.N. Baillie, A.C. McCarthy, S.R. Raine and C.P. Baillie at the National Centre for Engineering in Agriculture, University of Southern Queensland (Toowoomba). Their report “*Review of Precision Irrigation Technologies and their Application*” is available at:

   http://lwa.gov.au/files/products/national-program-sustainable-irrigation/npsi610/npsi610-precision-irrigation-final-report.pdf

3. Internationally, examples of commercial systems for control of variable applications (VRI) have tended to focus on linear moves and centre pivots due to their ease in retrofitting monitoring equipment. Centre pivot machines with the Farmscan 7000VRI system have been developed in Australia (http://www.farmscanag.com/) and a similar system has been developed in New Zealand by Precision Irrigation (http://www.precisionirrigation.co.nz). The New Zealand system was released into the market in 2008, and incorporates individual sprinkler control using wireless nodes and GPS technology.

   The Precision VRI system provides control of all sprinklers on a centre-pivot or lateral-move irrigator by individually pulsing sprinklers on and off, while controlling the irrigator speed to modify the application depth along the length of the irrigator. Control of irrigator speed and individual valves allows the amount of water applied to each area to be carefully regulated, optimising water application. For info visit: http://www.precisionirrigation.co.nz

4. Some useful recent videos on understanding precision irrigation are available at: http://www.precisionirrigation.co.nz/en/pages/video/

5. Innovation in irrigation: 12 Australia farming case studies http://nrmonline.nrm.gov.au/catalog/mql:432

3.2 Technological advances in irrigation management

This section highlights recent innovations in on-farm irrigation management, including scheduling, soil moisture mapping and the use of wireless sensor networks and precision irrigation systems.

- Advances in irrigation scheduling
- Soil moisture mapping
- Wireless sensor networks
- Precision irrigation management

The term “precision irrigation” here reflects the precision agriculture concept, applying GPS with sensors to prescribe inputs in the right place, at the right time and in the right amount.

Precision agriculture addresses in-field variability, largely ignored until the 1980s, and new GPS-enabled technologies have allowed precise irrigation management tools to enter the market (Hedley et al., 2013).

3.2.1 Closed loop irrigation systems

Capraro *et al.* (2008a, 2008b) utilized closed-loop irrigation control systems with moisture measurements in the root zone to maintain the soil moisture around a set value. More recently, Ooi *et al*. (2008) developed and tested an automated irrigation system for micro-irrigation. Two irrigation controllers – a soil-moisture based controller and an ET-based controller – were integrated into a wirelessly networked irrigation control system in an apple orchard and a commercial vineyard.

Results showed that automated irrigation using closed-loop control systems improved water productivity by 73% compared with manual irrigation (Uniwater, 2008). These results demonstrate the potential of 'closed-loop' irrigation control for irrigators at the lower end of the spectrum to 'leapfrog' rapidly to the upper end of the efficiency spectrum. For those irrigators already at the upper end, adoption of the technology would lead to substantial labour and time savings.

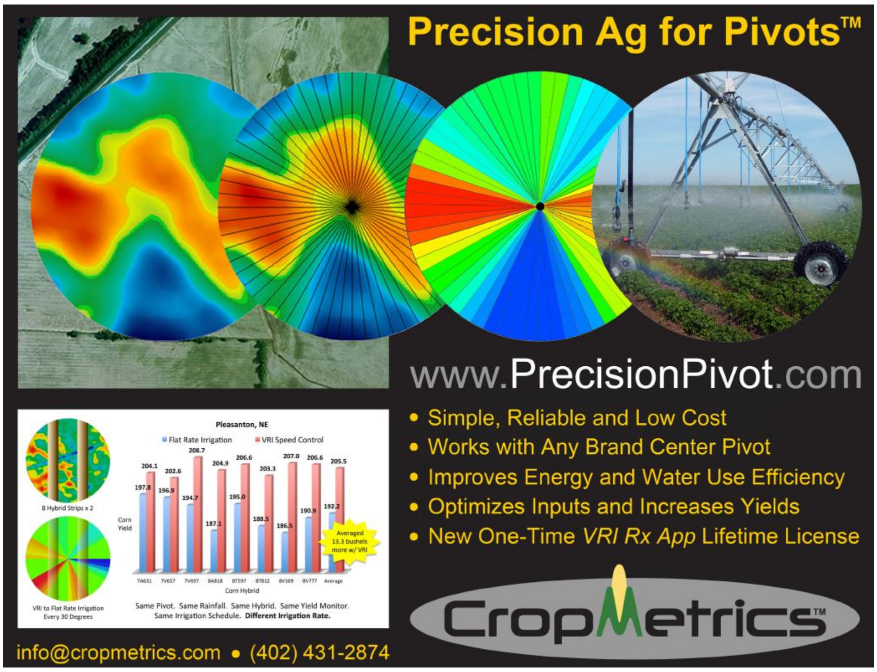
3.2.2 Advances in soil moisture sensing, wireless networks and precision management

1. Soil-moisture monitoring tools for triggering irrigation are perhaps the most widely used and most important tools for irrigation scheduling and a range of new improved sensors for monitoring soil water are now available (e.g. Cardenas-Lailhacar and Dukes, 2010).
2. Recent advances have been made to link soil moisture monitoring sites automatically to software decision tools linked to irrigation systems. For example, Blonquist *et al.* (2006) installed a soil-moisture sensor (time domain transmission) to log volumetric soil water content compared with an irrigation threshold, and connected this to a solenoid valve on the irrigation line supplying water to the irrigation system. This system applied 53% less water than under the conventional method. Kim *et al.* (2008) also linked soil moisture monitoring equipment to software control of a site-specific precision linear-move sprinkler irrigation system.
3. In Australia, a review of software tools for on-farm water management by Inman-Bamber and Attard (2005) lists a number of irrigation scheduling software packages that are increasingly being integrated into irrigation control via web and cellular control systems.

   http://www.irrigationfutures.org.au/imagesDB/news/CRCIF-TR-0205-web.pdf
4. Hornbuckle *et al*. (2009) described a remote sensing method for assessing within-field crop health variations (using NDVI) and links this to reference evapo-transpiration (ETo) values from nearby weather stations to provide field specific scheduling information. This crop coefficient derivation process uses a short message service (SMS) to provide information through a simple mobile phone text message service to irrigators on a daily basis. Such technologies enable real-time adaptive control systems for irrigation application (Smith *et al*., 2010). Adaptive control means that scheduling parameters are based on feedback from the process (Smith *et al.,* 2010) aiming for continued system improvements.
5. These scheduling methods assess crop and soil status, as well as other management effects – regional and some site specific – to improve scheduling tools. Site-specific measurements are obviously preferable. Examples of how these mapping tools can be combined with site-specific measurements to (a) optimise positioning of the sensors, and (b) provide a map of soil or crop condition to add further refinement to decision support tools and technologies for irrigation scheduling.
6. Hedley *et al.* (2012) used a wireless soil moisture sensor network optimally positioned into EM-defined management zones to inform a precision irrigation scheduling tool. Trials

in New Zealand have shown water savings are typically between 10 and 25% where variable soils occur under one system, and further savings are made by excluding irrigation from tracks, waterways, yards, sheds, and other unproductive areas (Hedley *et al*., 2011).

7. Management systems currently being developed alongside these precision irrigation systems include EM mapping to derive irrigation management zones with real-time soil moisture monitoring within each zone. For example, the Valley VRI system uses CropMetrics, a system that derives EM and landscape change layer to identify water-holding capacity variability across the field. These data layers are delivered through a "Virtual Agronomist", where the degree of field variability is used to decide on irrigation management strategies. The amount of variability relates to the amount of opportunity present, i.e. the higher the variability. the greater the opportunity for variable rate to benefit. Varying application rates increase input efficiency and improve yield production. For more information on the Valley Cropmetrics system, visit http://cropmetrics.com/features/valley-vri/



Booklet: http://cropmetrics.com/wp-content/uploads/CropMetrics-VRI-Brochure-2012-v2.pdf

8. Findings from a recent modelling study by Hedley *et al.* (2009) at five case-study sites in New Zealand found that where soil available water-holding capacity varied by 50 mm under one irrigation system then the potential water savings were about 10%, and variation by >100 mm gave a potential water saving of ≥15%. Savings are potentially greater in humid temperate regions (where some rainfall occurs during the irrigation season) in comparison with arid regions, where the main benefit of VRI for variable soils is a staggered start to irrigation at the beginning of the irrigation season, plus different watering strategies for soils of contrasting textural and drainage properties. Research has also been conducted to introduce wireless soil moisture sensor networks into EM and landscape-derived management zones for provision of real-time digital soil moisture information to the VRI controller. VRI control is established on site or remotely through a software package with internet or cellular connection.

9. Smart phone applications are being derived for irrigation control and management, which is often more suited to operational farmer use, than a computer sitting back in the farm office (e.g. www.waterbee.eu). The WaterBee system has been developed in Europe independently from a VRI system, with SME partners and is the result of a project

undertaken by a team of 10 partners from 8 European countries targeting a sustainable solution to contribute to reducing freshwater use by the agricultural sector. WSNs send readings to a soil-moisture model that automatically adapts irrigation requirements to different irrigation installations, and it is suggested that this WaterBee system will achieve real water savings while enhancing crop quality.

3.3 Developments in water resource management

3.3.1 Smart water metering

Knowing the amount of water being used and where it is used are important elements associated with practicing efficient irrigation. Typical pressurized irrigation farms are characterized by complex hydraulics due to numerous pipe fixtures and modifications that occur over time, and variable irrigation block flow delivery due to poor design and setup. Where flow monitoring occurs it is often conducted by manual readings of a water meter at irregular intervals.

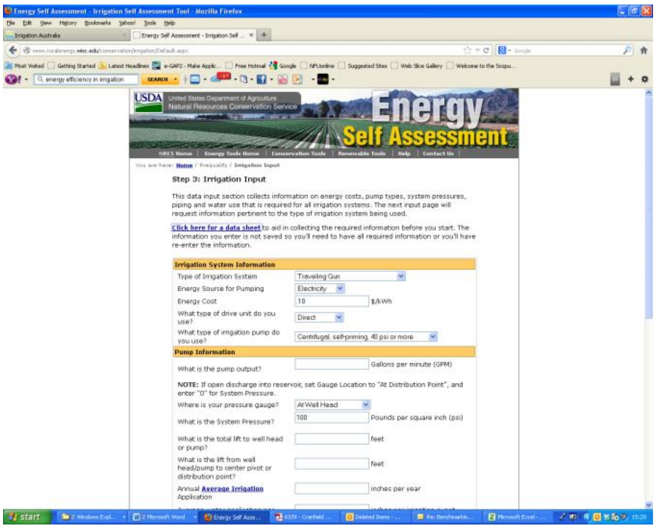
1. Smart irrigation metering involves the assessment of unique hydraulic characteristics at the source of a delivery system with multiple outlets (Pezzaniti 2009). This requires an ability to record and automate analysis of high frequency flow and pressure sensor data and allows not only for the continuous monitoring of water consumption but also for the identification of individual irrigation valve operation.

   Smart water meters have the following attributes (Giurco *et al.* 2008): real-time monitoring, high-resolution interval metering (≥10 seconds), automated data transfer (e.g. drive by, GPRS, 3G), and access to data via the internet or SMS. Most modern mechanical and electronic water meters and pressure sensors have features (e.g. pulse output) that allow flow to be monitored or logged. Hence, the implementation of smart water meters for monitoring on-farm irrigation typically involves the addition of a datalogger and/or communications to a traditional water meter and pressure sensor.

2. Coupling the identification of valve operation with the measured meter flows makes it possible to disaggregate the water flow so that any component within an irrigation system can be identified. This enables the flow and total volume applied to each irrigation block within the system to be recorded, providing comparative data for both the assessment of irrigation efficiency and the identification of maintenance and operating issues (e.g. pump wear, filter blockages, pipeline leaks and emitter variations). The water use information obtained may be used to improve irrigation design and practice. Similarly, the subsequent analysis of smart water meter data can be automated and integrated with controllers to optimise water, energy and maintenance requirements.

3.3.2 Energy audits and self-assessments for irrigated agriculture

There are an increasing number of websites available to assess energy costs and opportunities to reduce energy use in irrigated agriculture. These require data to be collected and input information on energy costs, pump types, system pressures, piping and water use that is required for all irrigation systems. For example http://www.ruralenergy.wisc.edu/conservation/irrigation/Default.aspx



3.3.3 Digital advances in cloud computing and remote sensing

Alongside innovations in irrigation systems and soil moisture monitoring, digital advances using the latest cloud computing technologies are also moving into precision agriculture. Cloud computing involves using networks of remote servers hosted on the internet to store, manage, and process data, rather than hosting information and data on local servers. They generally rely on wireless data transfer and mobile web applications, in combination with other tools and spatial technologies including GPS and GIS. Cloud technology is well established within data-intensive industries, but only recently emerging in agriculture where various applications are being marketed. For example, in the USA, cloud services provide on-farm support from agribusinesses and consultants, for agrochemical application management. Other precision-related tools are now emerging.

New uses relating to precision irrigation include applications for mobile devices operating in the cloud to spatially monitor soil moisture, crop growth, and irrigation in real-time via in-field sensor arrays. Other cloud uses include providing data to refine planting and harvest operations, by integrating GPS and GIS data or managing equipment performance (pressures, flow rates, abstractions) at district or catchment scales. Radio-frequency identification tags (RFID), which automatically download data, are also becoming more widespread in agriculture. For example, tagging systems have been developed to collect data on straw bale moisture content, weight and in-field position (GPS); in the future, similar cheap, possibly biodegradable, micro-tags could be deployed across fields to measure seasonal changes in soil moisture, organic content, crop canopy development, and canopy stress, or for monitoring and optimizing energy needs across pressurized irrigation distribution networks (Carrillo Cobo *et al*. 2011). However, data security issues relating to confidentiality, integrity, availability, and accountability still need to be resolved before cloud technology can be fully integrated into precision irrigation.

There is also increasing potential for new applications linking the use of high resolution and high frequency remote sensing data (e.g. MODIS) to inform on-farm irrigation management, including mapping croplands, and monitoring spatial changes in crop cover in support of farm monitoring of irrigation water use and evapotranspiration (ET) (Thenkabail *et al*., 2011). Recent remote sensing developments provide scope for mapping croplands in a routine, rapid, and consistent way, with sufficient accuracy (Congalton and Green, 2009). There is also potential to use remote sensing to identify irrigated regions where improvements in water productivity should be targeted to reduce ‘yield gaps’ (Fereres *et al*., 2011). By integrating advanced technologies such as cloud computing with developments in precision irrigation and remote sensing, there is also broader scope to improve our understanding of the links between food production and water scarcity, and the impacts of climate change on food supplies.

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