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Improving irrigation efficiency:
Raingun performance in field scale vegetable production

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Abstract

In England and Wales, rising demands on water resources and competition between sectors is leading to increased pressure on field vegetable growers to irrigate more efficiently. Approximately 40,000ha of field scale vegetables are irrigated in England and Wales in a dry year. Between 60% and 90% of this area is estimated to be irrigated using hose-reels fitted with rainguns. However, despite their popularity, these systems are inherently non-uniform in water distribution, particularly in windy conditions. Improving their application uniformity has therefore been identified as one of the most practical solutions to increasing irrigation efficiency for field vegetable growers.

This thesis develops an integrated approach to model the spatial and temporal impacts of irrigation non-uniformity on the yield and quality of a vegetable crop grown in the UK. The research used carrots as a representative crop because of their sensitivity to irrigation and high importance within the field vegetable sector. The impacts of a range of raingun equipment and management strategies (field orientation, lane spacing, sector angle, night versus day irrigation) have been evaluated.

Two models were used to simulate raingun irrigation. “TRAVGUN” was first used to generate a database of wind affected wetted patterns for a typical raingun system. “TRAVELLER” then simulated raingun movement down and across a field, applying these patterns according to ambient wind conditions and a pre-defined range of equipment and management strategies. Carrot yield response to spatially variable irrigation was simulated using the model “Carrot Calculator”. A spreadsheet model was also developed to quantify the impacts of irrigation non-uniformity on carrot quality. The models were calibrated and validated using data collected during 2003 and 2004 from field sites on commercial farms in East Anglia.

The outputs from the research include new information, datasets and detailed maps showing the spatial and temporal patterns of irrigation application and their consequent impacts on crop yield and quality. The findings demonstrated that the raingun equipment and management strategies employed by growers can have a considerable impact on application uniformity, and hence on crop production. Of particular importance were the closely linked variables of lane spacing and sector angle. The analyses suggested that the highest application uniformity occurred using a lane spacing of 70 m and a sector angle of 210° where wind speeds were <2 m s^{-1}. At higher wind speeds, narrowing the lane spacing to 60 m and using a sector angle of 180° (or 210° where the wind speed was greater than 3 m s^{-1}) provided maximum uniformity. If the lane spacing cannot be altered from 70 m, increasing the sector angle to 240° at higher wind speeds improved uniformity. The industry recommended lane spacing of 72 m may therefore be marginally too wide, particularly under windy conditions. The research also confirms that orientating fields/travel lanes perpendicularly to the prevailing wind direction and irrigating at night when wind speeds are typically lower can help reduce application non-uniformity. These findings have helped to substantiate many of the measures being widely discussed for improving irrigation efficiency. The integrated approach has also enabled the combination of various equipment and management strategies to be more thoroughly evaluated than was previously possible.

Irrigation uniformity was found to have a considerable impact on carrot crop yield and, in particular, quality. For example, in a typical dry year, simulated non-uniform irrigation resulted in a total yield loss of 4%, a marketable yield loss of 8% and a premium root yield loss of 11%. This could have resulted in an income loss of approximately £288-585 ha^{-1} (4-8%). Importantly, and contrary to grower perceptions, this research demonstrated that a small but appreciable crop loss (up to 1%) may occur due to just a single non-uniform irrigation during critical crop growth periods.

This research has provided useful insight and new information in support of developing recommendations to assist growers not only in improving their crop production but also in demonstrating efficient irrigation both for meeting grower protocol requirements and at abstraction licence renewal. In addition, the findings will help inform the regulatory authorities on the complexities and difficulties of achieving efficient irrigation. The research approach could also be readily utilised by manufacturers to assist in designing and improving raingun equipment. Although the modelling approach was developed for raingun irrigated carrots, the methodology could be readily extended to other crops and overhead irrigation systems to provide tools for growers and the crop services industry to evaluate system performance and the impacts for crop production.

Keywords: irrigation; raingun; uniformity; efficiency; horticulture; carrots; modelling.

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1. Introduction

This chapter describes the context for this research by explaining the current drivers for improving the efficiency of agricultural irrigation in England and Wales and the measures by which such improvements might be attained. The benefits of agricultural irrigation in the UK, the current usage and the underlying trends are first described. A summary of irrigation water resource issues in England and Wales including the regulatory context and legislative drivers for improving irrigation efficiency are then presented. Finally, the research problem, the aims and objectives, the research approaches and the dissertation structure are outlined.

1.1. Benefits of irrigation, current usage and underlying trends

The UK agricultural industry is increasingly reliant on irrigation as an essential component of crop production. During the summer months, many crops can experience water shortages which may limit production. This is particularly the case for crops grown on light soils in areas where rainfall is low (typically <350 mm during April to September). Consequently, supplemental irrigation is commonly applied to outdoor crops (particularly high value crops) in these situations. The benefits of irrigation in relation to crop yield and quality, and the current usage and underlying trends in UK agricultural irrigation are summarised below.

1.1.1. Crop yield and quality

Supplemental irrigation in the UK has the potential to significantly increase both crop yield and quality. However, the extent to which irrigation can benefit crop production will depend on crop type and variety, climate variation during the growing season, soil type and management practices.

In their detailed study of the costs and benefits of irrigation in East Anglia, Morris *et al.* (1997) provided estimates of crop yield and quality response to irrigation in the UK, based on industry advice and experimental data by ADAS (1977) and MAFF (1984) (Table 1.1). Crop yield responses were estimated to vary from 0.02-0.03 t ha^{-1} mm^{-1} (e.g. grass, cereals, orchard and soft fruit) to 0.08-0.14 t ha^{-1} mm^{-1} (e.g. potatoes, root vegetables, onions and cabbage). Morris *et al.* (1997) also estimated the price benefit of assuring quality produce through appropriate irrigation for three soil available water capacities (AWCs) – high, medium and low (Table 1.1). Their analysis showed that the benefits of irrigation for attaining premium crop quality (primarily uniformity, size and appearance) can be very important for certain high value crops (e.g. potatoes, most vegetables and fruits), especially when grown on droughty soils and/or during dry seasons.

Table 1.1 *Crop yield response to and quality benefits of irrigation (Morris et al., 1997).*

Crop	Yield response (t ha^{-1} mm^{-1})	Quality assurance price benefit (%) for soil with:			Dominant quality indicator
		High AWC	Medium AWC	Low AWC	
Maincrop potatoes	0.08	25%	30%	40%	scab
Early potatoes	0.08	11%	23%	40%	scab
Sugar beet	0.13	0%	0%	5%	processing quality
Cereals	0.02	0%	0%	5%	n/a
Peas - dried	0.04	11%	18%	25%	uniform size and colour
Peas - vining	0.04	11%	16%	25%	uniform size and colour
Carrots	0.13	6%	15%	30%	shape, colour and cracks
Parsnips	0.13	3%	6%	10%	uniform size and shape
Beetroot	0.13	8%	13%	20%	scab, shape and colour
Turnips - culinary	0.13	2%	8%	10%	taste
Swede - culinary	0.14	0%	0%	0%	n/a
Celery	0.08	40%	40%	50%	blackheart
Leeks	0.08	7%	13%	20%	length, diameter variability
Cabbage - spring	0.14	4%	7%	15%	size, head compacness
Calabrese	0.05	5%	12%	20%	uniformity
French beans	0.06	9%	17%	25%	uniform size and colour
Runner beans	0.05	9%	16%	25%	uniform size and colour
Brussels sprouts	0.04	6%	14%	25%	firmness, uniformity
Cauliflower	0.07	6%	14%	25%	discolouration
Lettuce - outdoor	0.05	40%	40%	50%	tip burn
Bulb onions	0.08	14%	24%	40%	skin, size
Salad onions	0.08	13%	20%	30%	uniformity
Radish	0.03	3%	8%	10%	splitting
Asparagus	0.02	6%	16%	30%	uniformity
Grass - grazing	0.03	0%	0%	5%	digestibility
Grass - silage	0.03	0%	0%	5%	digestibility
Strawberries	0.03	0%	11%	20%	bright, uniformity
Raspberries	0.03	0%	11%	20%	size, seediness
Blackcurrants	0.03	0%	11%	20%	size
Rhubarb (in open)	0.05	3%	8%	10%	size, turgidity
Dessert apples	0.02	14%	20%	25%	skin, size
Pears	0.03	8%	14%	20%	shape colour
Plums	0.02	8%	14%	20%	skin, shape

Although yield increases due to irrigation are important, in the last decade the emphasis of irrigation has switched towards ensuring quality produce and continuity of supply. One of the main drivers for this change has been the increasing pressure on growers from the major processors and supermarkets to provide a reliable supply of premium quality produce. These demands are usually stipulated through grower protocols (e.g.

Tesco's "Nature's Choice") as part of supply contracts. Other contracts (for example with pack-houses or processors) may only pay growers for the marketable produce harvested. Carefully managed irrigation is therefore required by growers to maintain crop uniformity, improve visual appearance and reduce certain disease risks (e.g. common scab in potatoes and carrots). Without the yield and quality benefits provided by appropriate irrigation, growers can suffer major financial penalties and may struggle to secure and maintain contracts with their markets.

1.1.2. Irrigated areas and volumes applied

Surveys of the extent of irrigated agriculture in England and Wales have been carried out since 1955 by the Ministry of Agriculture, Fisheries and Food (MAFF), now the Department for Environment, Food and Rural Affairs (DEFRA). The most recent and directly comparable surveys were carried out in 1982, 1984, 1987, 1990, 1992, 1995 (England only) and 2001, and are summarised in Weatherhead and Danert (2002a,b). The surveys provide information on the areas of crops irrigated, the volumes of water applied, the dry year position assuming adequate water supply, the sources of irrigation water, water storage (except 2001 survey) and the types of irrigation equipment used.

The main irrigated crops in England and Wales, and the proportion of the total crop areas which were irrigated in 2001 are summarised in Table 1.2. In 2001, approximately 3,977,000ha of the 11,350,000 ha of agricultural land in England and Wales was used for crop production; of this cropped area, only 149,000 ha (4%) was irrigated (Weatherhead and Danert, 2002a,b; DEFRA, 2002; DEFRA, 2006a; National Assembly for Wales, 2006). The most commonly irrigated crops were potatoes (early and maincrop), vegetables and small fruit; irrigation was a widespread practice within these crops. Irrigation of other crop sectors was much less widespread; for example only 6% of sugar beet and orchard fruit were irrigated in 2001 and less than 1% of grass and cereals.

The majority of the irrigated area in England and Wales is concentrated in the east and south of the mainland where there tends to be fertile, easily worked soils, but below average summer rainfall (Bailey, 1990). In 2001, 54% of the irrigated area was located in the Environment Agency's Anglian region, with a further 19% in the Midlands region, 10% in the Southern region, 7% in the North East and 6% in Thames. The North West, South West and Wales regions each accounted for only 1% of the total irrigated area (Weatherhead and Danert, 2002b).

Table 1.2 *Estimated area of the main irrigated crops in England and Wales (2001) and proportion of the total crop area which was irrigated (Weatherhead and Danert, 2002a,b; DEFRA, 2006a; National Assembly for Wales, 2006).*

Crop category	**Total cropped area (ha)**	**Irrigated area (ha)**	**Proportion irrigated (%)**
Early potatoes	12,575	7,699	61
Maincrop potatoes	116,440	70,943	61
Sugar beet	177,340	9,758	6
Orchard fruit (e.g. apple, pear)	26,411	1,657	6
Small fruit (e.g. strawberries, raspberries, blackcurrants)	7,606	3,898	51
Vegetables (e.g. carrots, parsnips, onion, leek, brassicas, lettuce, fresh peas and beans)	107,633	39,233	36
Grass	743,049*	4,119	0.6
Cereals	2,533,756	4,619	0.2
Other (e.g. ornamentals, herbs, flowers)	n/a	7,293	n/a
Total	**3,977,103**	**149,218**	**3.8**

* Grass <5 years old; it is assumed that pasture >5 years old is unlikely to be irrigated

Figure 1.1 and Figure 1.2 illustrate the recent trends in irrigated area and volume by crop sector for England and Wales between 1982 and 2001. Note that the irrigated areas and volumes applied are strongly influenced by the prevailing weather in each year – in general terms, 1987, 1992 and 2001 were wet years, 1982 and 1984 were average years and 1990 and 1995 were dry years. In addition, it is important to observe that there can be relatively large regional variations in the composition of irrigated areas and volumes applied. In some regions, specific crops dominate local land use, such as potatoes in Pembrokeshire, orchard fruit in Kent and field vegetables and sugar beet in certain areas of East Anglia.

The total irrigated area in England and Wales has seen a gradual increase from 103,500 ha in 1982 to nearly 150,000 ha in 2001. Over this period there have been substantial changes in the composition of the irrigated area, driven mainly by rising production costs, changes in agricultural policy and international market demands which have impacted on the economic feasibility of irrigating certain crops. As a result, the area of irrigated low value crops such as cereals and grass has diminished by nearly

75% over the 19 years. Conversely, the irrigated area of high value crops such as vegetables and maincrop potatoes have seen a dramatic rise of 260% and 300% respectively. The area of most other irrigated crop sectors has remained relatively stable during this period with the exception of sugar beet which has seen marked fluctuations, largely due to climatic variations and changes in market conditions.

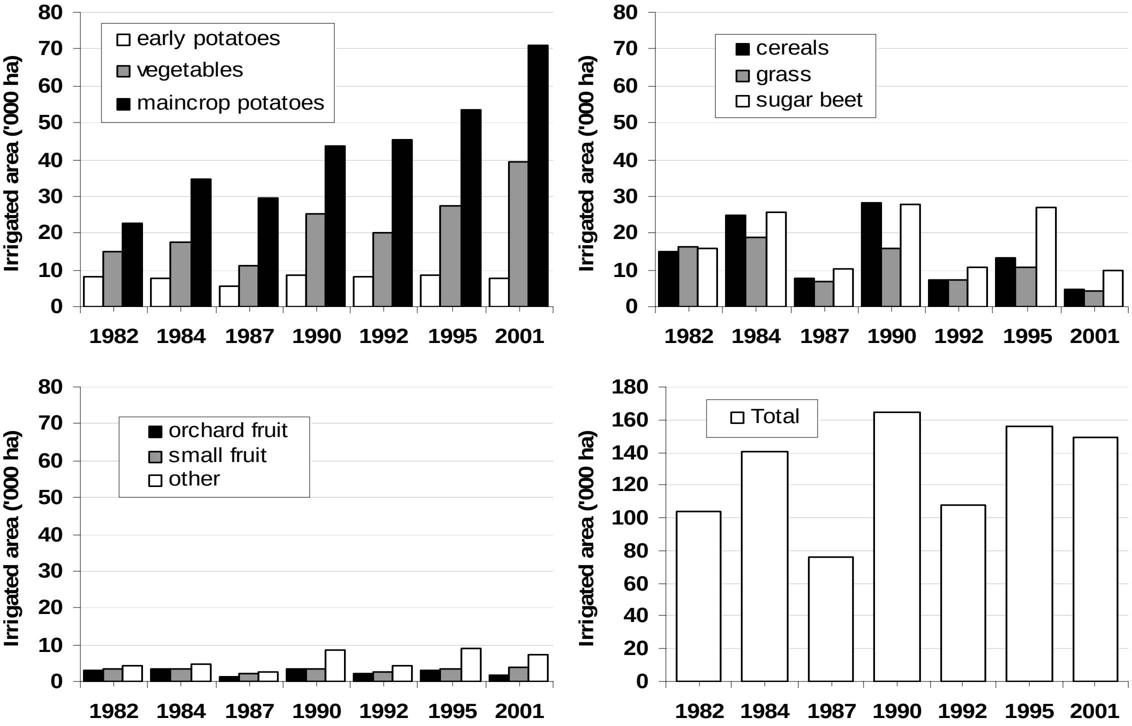

Figure 1.1 *Recent trends in irrigated area (ha) by crop sector for 1982-2001. Note that 1995 data was for England only (Weatherhead and Danert, 2002a,b).*

The volume of irrigation applied in England and Wales has seen an underlying growth of approximately 3% per annum from 1982-1995 (Weatherhead and Knox, 2000), with a current (2001) annual demand of 133 M m^3 (Figure 1.2). This increase was partly a consequence of the larger irrigated area by 2001, but was also a result of an increase in the average amount of water applied (533 m^3 ha^{-1} in 1982 rising to 889 m^3 ha^{-1} in 2001). In particular, almost all high value crops have seen a strong rise in average seasonal application depths. For example, the average depth of irrigation applied to vegetables rose from 46 mm in 1982 to 93 mm in 2001. However, the average application on low value crops has remained relatively constant or decreased (e.g. the application depth for cereals was 34 mm in 1982 and 32 mm in 2001). Although the desire to boost yield of high value crops has been partly responsible for this change, the function of irrigation in securing reliable supplies of quality produce has become an increasingly important driver (e.g. Aitken *et al.*, 2004).

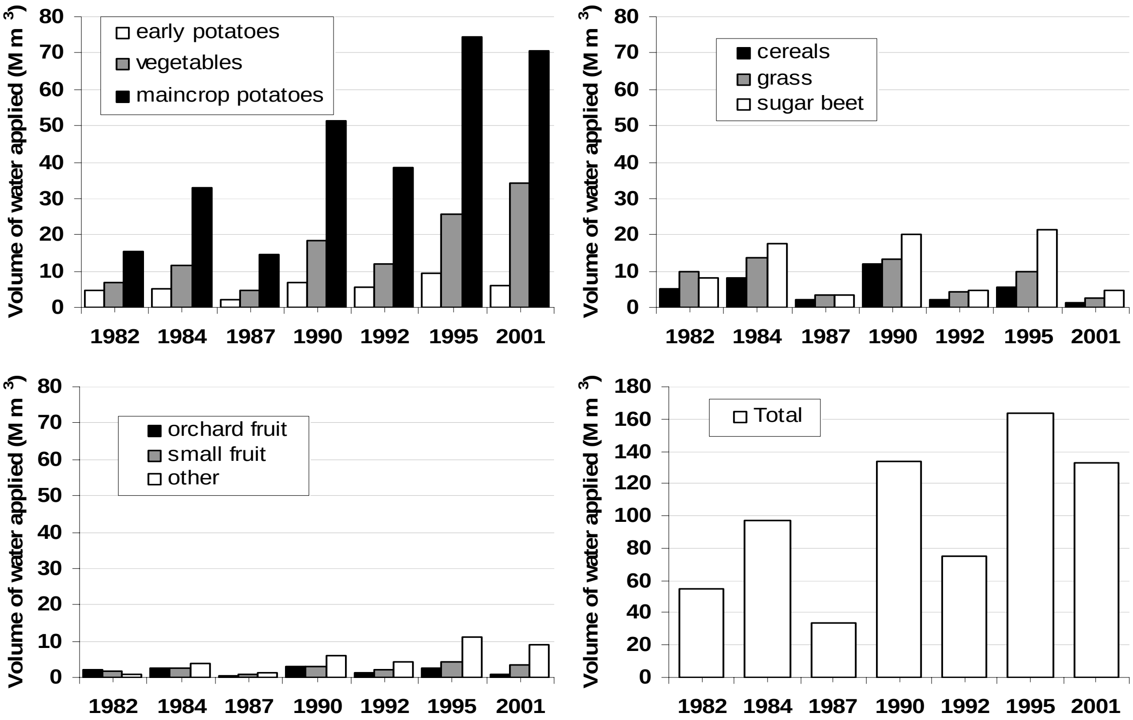

***Figure 1.2** Recent trends in irrigated volume (M m^3) by crop sector for 1982-2001. Note that 1995 data was for England only (Weatherhead and Danert, 2002a,b).*

In contrast to England and Wales, irrigation surveys in Scotland have been infrequent and irregular, reflecting the small extent of irrigated agriculture in that country. An unpublished survey was carried out in 1982 for the Department of Agriculture and Fisheries for Scotland and the most recent survey was carried out in 2000 by the Scottish Agricultural College (SAC, 2001) and reported by CJC (2002). No irrigation surveys are known for Ireland, but owing to the relatively wet climate, the extent of irrigation is unlikely to be significant (Holden *et al.*, 2003).

For the last survey date (2000), irrigation in Scotland was restricted to 7,300 ha mainly in Angus, the Borders, East Lothian, Fife and Perth and Kinross regions. The majority of irrigation was applied to potatoes (early, maincrop and seed), but vegetables and soft fruit were also important irrigated crops (CJC, 2002).

1.1.3. Equipment usage

In 2001, 95% of the irrigated area in England was reported to receive overhead irrigation, with hose-reels fitted with rainguns comprising 72% of the total. Hose-reels fitted with booms were used to irrigate 16% of the area and sprinklers, spray lines, linear moves and centre pivots constituted the remaining 7% of overhead systems. Trickle or drip irrigation was used on 5% of the irrigated land (Weatherhead and Danert, 2002a). A more recent survey by Knox and Weatherhead (2005) suggested that trickle irrigation might account for as much as 10% of the irrigated land, although the survey methods were not directly comparable. Irrigation equipment usage in Scotland in 2000 followed a similar pattern, with 95% of crops reported to receive overhead irrigation, of which the majority was applied using hose-reel rainguns (Aitken *et al.*, 2004).

Hose-reels fitted with rainguns have become the predominant irrigation system in the UK due to their relatively low capital costs, ease of use, ability to irrigate uneven shaped fields and flexibility to fit varying crop rotation and scheduling requirements. However, hose-reel raingun systems are prone to non-uniform water application, particularly in windy conditions (e.g. Schull and Dylla, 1976a,b; Arshad Ali and Barefoot, 1984; Dalvand, 1986; Musa, 1988; Richards and Weatherhead, 1993; Grose, 1999). Uniform irrigation is considered crucial to maximising both yield and quality of a crop. Non-uniform application of water can lead to areas of soil water shortage and/or excess which can result in uneven crop growth with implications for crop quality.

Although there appears to be a trend towards the increased use of more uniform irrigation systems such as trickle or hose-reels fitted with booms it is likely that for the foreseeable future, hose-reel raingun systems will remain the dominant form of irrigation for the main UK crop sectors (Pullen, 2006). This is mostly due to concerns regarding the economic viability of farming which is acting as a deterrent to growers from investing in costly alternative irrigation systems. Additionally, many of these alternative systems can be unsuitable for the variety of field morphologies, crop types and crop rotations typical of UK irrigated agriculture.

1.2. Water resources and regulation

Although nearly a quarter of all abstraction licences in force in England and Wales in 2003 were for agricultural spray irrigation, the annual volume of water abstracted by the sector (estimated by the regulatory authority, the Environment Agency) accounts for less than 1% of the total abstracted volume (DEFRA, 2005a) (Table 1.3)[1]. However, because irrigation is a largely consumptive use of water which is concentrated in the driest areas in the driest months, it can become the largest abstractor in some catchments in summer months (Knox *et al.*, 1997; Downing *et al.*, 2003).

In 2001, nearly 60% of the water abstracted for irrigation was sourced from surface water, with a further 36% from ground water (Weatherhead and Danert, 2002a). The majority of irrigation water is typically used directly from source, with relatively little on-farm storage (Knox *et al.*, 1997). Irrigation can therefore place significant demands on summer water resources in certain areas, resulting in reduced river flows and low water levels in standing waters and aquifers. This has led to widespread concern over the potential impact of over-abstraction for irrigation on the environment and for other water users (e.g. RSPB, 1995; EA, 2001; EA, 2002; EA, 2005).

Table 1.3 *Number of abstraction licences in force and the licensed and estimated actual abstraction by water use sector in England and Wales for 2003/4 (DEFRA, 2005a)[1].*

Sector	**Number of abstraction licences in 2003/4**	**Licensed abstraction volume in 2003 (Ml d^{-1})**	**Estimated actual abstraction in 2003 (Ml d^{-1})**	**% of total abstraction in 2003**
Electricity supply	364	76,436	31,378	53.6%
Public water supply	1,774	27,354	16,920	28.9%
Other industry	5,849	15,511	6,623	11.3%
Fish farming, cress, amenity ponds	778	5,438	3,077	5.3%
Spray irrigation	**11,560**	**933**	**315**	**0.5%**
Agriculture (excl.spray irrigation)	22,464	352	132	0.2%
Other	194	449	86	0.1%
Private water supply	3,619	122	61	0.1%
TOTAL	**46,602**	**126,596**	**58,593**	**100%**

In addition to the underlying 3% per annum growth in irrigation demand (Weatherhead and Knox, 2000), the latest climate change forecasts suggest that the dry year demand

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[1] Note that the EA defines irrigation differently to the MAFF and DEFRA irrigation surveys, so direct comparison of abstraction volume estimates are not expected to agree.

for irrigation water in England and Wales may increase by around 30% by 2020 and by about 55% by 2050 (Downing *et al.*, 2003). However, as water demands are forecast to increase, supplies are expected to decrease. Summer river flows are predicted to be reduced by around 30% by 2020 (Arnell, 2004) and groundwater recharge in East Anglia is predicted to decrease by approximately 10% by 2020 and by about 25% by 2050 (Weatherhead *et al.*, 2005). These forecasts are generating serious concerns regarding the future reliability and sustainability of water resources for irrigation, particularly in south-east England where the supply-demand imbalance is most pronounced. To cope with these likely changes in water availability, growers will need to improve their irrigation efficiency, and are likely to have to consider other adaptive strategies such as on-farm winter storage, water trading and changes to cropping practices (Weatherhead *et al.*, 2005).

Abstraction of almost all water in England and Wales including irrigation (though not currently trickle irrigation) is controlled by licensing through the regulatory authority, the Environment Agency (EA). The abstraction licensing process was established through the Water Resources Act 1963 which granted abstractors permanent “Licences of Right”. Although the process was amended slightly through the Water Resources Act 1991, the basic structure of abstraction licensing remained in place until concerns about over-abstraction and poor regulation led to a review of the system in the late 1990s (DETR, 1999). This review and the influence of the European Water Framework Directive 2000/60/EC have led to the development of Catchment Abstraction Management Strategies (CAMS) and the Water Act 2003.

CAMS are being developed to allow the water supply-demand balance of each catchment to be reviewed in consultation with stakeholders on a 6-year cycle, providing detailed information to assist the EA in abstraction licensing (EA, 2002). The CAMS process began in 2001, and the EA aim to have a CAMS in place for all catchments by 2008. In addition to their water resource allocation function, CAMS provide a useful link with other initiatives such as Catchment Flood Management Plans and Biodiversity Action Plans and will also assist in the implementation of River Basin Management Plans for the Water Framework Directive.

The Water Act 2003 will effect a number of changes to the licensing system: all irrigation (including trickle) will have to be licensed, licences will be time-limited to coincide with the CAMS reviews (based on a 12-year cycle) and the EA will have much greater powers to prevent, limit or revoke abstraction licences for environmental protection reasons. The new time-limited licences will have a presumption of renewal, subject to three key tests (EA, 2005):

i) *Continued environmental sustainability* – unsustainable abstraction will be identified by the EA through the CAMS process and appropriate action taken;

ii) *Continued justification of need* – licence holders will be obliged to demonstrate continued requirement for abstraction, and that their maximum potential levels of abstraction remain reasonable. In the case of irrigated agriculture, this will need to be re-assessed following any marked changes in irrigation practice, crop area and/or type and climate;

iii) *Efficient use of water* – licence holders will be required to demonstrate that the water they abstract is used efficiently (i.e. "the right amount of water in the right place at the right time" (EA, 2005)). Regular water auditing (at a frequency determined by the demand on water resources in the catchment) is likely to provide one of the tools for abstractors to demonstrate best practice water use.

If licence holders fail to meet any of the three tests, the EA have the power to restrict abstraction volumes or rates on the licence or even refuse licence renewal altogether.

In addition to the new regulatory requirements for abstraction licence renewal, growers are increasingly facing pressure from other sources to demonstrate more sustainable resource use (including water). For example, multiples (primarily supermarkets) are responding to increasing public demand for food which is sustainably produced. Contracts with growers incorporate protocols such as Tesco's "Nature's Choice" and Marks and Spencer's "Field-to-Fork". These protocols not only stipulate produce quality and supply requirements, but also oblige growers to demonstrate best environmental practice. In addition, some supermarkets favour growers who adopt schemes such as the Assured Produce Scheme (part of the Assured Food Standards organisation) or the LEAF (Linking Environment and Farming) Marque. These contracts require that growers comply with acceptable environmental standards for crop production – i.e. using resources efficiently, including water for irrigation.

1.3. Improving irrigation efficiency

It is therefore clear that irrigated agriculture in the UK is facing increasing pressure to improve its efficiency of water use both from regulatory authorities and consumers. It is also apparent that the uptake of irrigation systems which can help improve efficiency (such as hose-reel booms and drip/trickle systems) is likely to remain limited for the foreseeable future. Enhancing irrigation efficiency should therefore focus on improving the most widespread irrigation system – hose-reels fitted with rainguns.

There are two fundamental approaches to improving the efficiency of water use in irrigated agriculture: either reducing the water volume supplied to a crop without detriment to yield or quality, or increasing the crop production without an increase in water volume supplied to it. Both approaches ascribe to the widely accepted advice that achieving more sustainable water use for irrigated agriculture relies on growers obtaining more “crop per drop” (FAO, 2002). A summary of potential methods for improving efficiency in raingun irrigation and their limitations is presented in Table 1.4.

With reference to UK irrigated agriculture, the most applicable approaches to improving the efficiency of raingun irrigation identified in Table 1.4 are to improve scheduling accuracy and reduce application non-uniformity. Improving irrigation scheduling is, in theory, a relatively straight-forward task, since growers now have access to an increasing array of scheduling equipment, computer programs or contracted services. However, the practically feasible strategies available for reducing raingun application non-uniformity and the potential impacts this may have on crop yield and quality are little understood by growers. Many operate their rainguns on factory settings or “gut instinct” and do not account for wind effects on uniformity in their irrigation strategy (e.g. Augier *et al.*, 1996, Smith *et al.*, 2002). Consequently, the uniformity of raingun irrigation in the UK is likely to be sub-optimal. This results in reduced irrigation efficiency with potential implications for crop production, for meeting grower protocol demands and for abstraction licence renewal.

Table 1.4 *Potential approaches and limitations (italics) to improving the efficiency of raingun irrigation*

Reducing water volume supplied (without detriment to crop yield or quality)	**Increasing crop production** (without increasing water volume supplied)
Eliminate distribution/conveyance losses Preventing losses from channels and pipes carrying water from source to field will ensure that all abstracted water is applied to the crop. *In practice, such losses can be difficult to resolve without large capital investment – e.g. channel lining or replacement. In the case of the pressurised mains systems favoured by large irrigators, leakages tend to be negligible.*	**Change microclimate** Crop growth can be encouraged by using plastic or fleece to increase temperature or CO_2 levels. *However, this approach is costly and can only be justified for early-season crop production when premiums are high (Weatherhead et al., 1997)*
Reduce evaporative and spray drift losses during irrigation Evaporative and spray drift losses from overhead irrigation may be as high as 40% (e.g.Tarjuelo *et al.*, 2000). Reductions may be achieved through adopting techniques such as night-time irrigation. *However, night-time irrigation is not always practicable and there are limits to the potential reductions in evaporation and spray drift from overhead irrigation.*	**Optimise nutrient and pesticide practices** Crop yield and quality can be maximised through appropriate management of nutrients and pesticides *However, many growers are already operating at or near optimal crop nutrient and pesticide regimes. Higher applications are likely to increase costs and risk watercourse pollution, without significant marketable yield benefits.*
Improve scheduling accuracy By tailoring water applications more accurately to crop requirements, total volumes applied may be reduced (e.g. Stalham *et al.*, 1999) *However, more accurate scheduling may reveal greater crop irrigation requirements than currently recognised. Improved scheduling also requires considerable labour and/or financial inputs.*	**Use cultivars with greater "water use efficiency" or scab resistance** Some crop varieties may have higher drought tolerance and/or are less susceptible to scab infection at low soil moisture levels. *However, trials in this area for the main irrigated crops have only recently started at HRI Kirton, currently restricted to brassicas.*
Reduce application non-uniformity By reducing the extent of areas with excess applied water and water deficit, the volume of water required to apply the desired minimum depth of irrigation to a crop can be reduced. *However, there are practical limitations to reducing non-uniformity since all overhead irrigation systems are subject to wind effects.*	**Reduce application non-uniformity** By reducing the extent of areas with excess applied water and, in particular, water deficit, it should be possible to increase crop yield and quality with no net increase in water supplied. *However, there are practical limitations to reducing non-uniformity since all overhead irrigation systems are subject to wind effects.*
Reduce evaporative losses from soil Mulching bare soils to reduce soil evaporation may have some benefits in reducing water inputs. *However, for the majority of crops, this is not always practical or cost-effective.*	
Increase rooting depth Increasing the rooting depth of plants by minimising compaction and plough-pan formation or using deeper rooted varieties would allow crops to access greater soil water reserves (Weatherhead *et al.*, 1997) *However, growers practicing good soil management should already have minimised compaction or pan problems, and commercial crops are not generally selected for beneficial rooting structures.*	

Many researchers have established a connection between non-uniform irrigation and yield and/or quality losses (e.g. Stern and Bresler, 1983; Dagan and Bresler, 1988, Ayers *et al.*, 1990, 1991; Or and Hanks, 1992; Barber and Raine, 2001; Ruhle, 2002; Baillie, 2002; Buendia-Espinoza *et al.*, 2004). However, a few studies have not found a particularly strong link (e.g. Mateos *et al.*, 1997; Sanden *et al.*, 2000; Koech, 2003). Reducing irrigation non-uniformity and its consequent impacts on crop yield and quality is therefore widely accepted as critical to achieving efficient use of the increasingly limited water resources available to irrigated agriculture.

Many researchers have examined the causes of raingun irrigation non-uniformity and suggested options for improvement through changing equipment settings or management strategies (e.g. Schull and Dylla, 1976a,b; Oakes and Rochester, 1981; Arshad Ali and Barefoot, 1984; Denton, 1985; Hipperson, 1985; Dalvand, 1986; Rahmeto, 1987; von Bernuth, 1988; Smith *et al.*, 2002; Growcom, 2004a). However, there has only been limited investigation into the impacts this may have on crop production. For example, Musa (1988) and Al-Naeem (1993) both simulated the impacts of non-uniform raingun irrigation on potato yield (but not quality) in the UK using relatively simple models. Similarly, Bruckler *et al.* (2000), Lafolie *et al.* (2000) and Ruelle *et al.* (2003) modelled the impact of non-uniform raingun irrigation on maize yields in France and Cemagref (1999) simulated the impact on wheat yields in the UK.

In particular, the UK field vegetable sector has suffered from a lack of strategic research that focussed on assessing the factors that affect raingun non-uniformity and the consequences of this for crop production. To date, research in this area has only been restricted to small-scale farm trials in the UK by Revaho (2005) and in Australia by Koech (2003). Revaho (2005) demonstrated a slight (but not statistically significant) increase in carrot yield and quality as a result of sprinkler irrigation compared to traditional raingun systems. However, no measurement of irrigation system uniformity was made in this trial and no scientific replication was reported. Koech (2003) also investigated carrots irrigated with sprinklers and raingun systems, but found no significant link between non-uniformity and total or marketable yields. Neither trial directly measured the impacts of spatial and temporal irrigation non-uniformity on crop production, nor did they evaluate the potential benefits of changing equipment and/or management strategies for improving irrigation efficiency.

1.4. Summary of research problem

Improving irrigation efficiency is a critical issue for growers. This is not only to improve the yield and quality of produce in order to secure contracts with multiples, but also to meet the requirements of grower protocols and abstraction licence renewal. In the UK, one of the key approaches to improving irrigation efficiency lies in reducing the application non-uniformity of hose-reel rainguns. Although there has been considerable previous research into raingun operation, there has only been limited investigation of the impacts which this may have on crop production, particularly for the field vegetable sector. Hence, there is a need to investigate the impacts of non-uniform irrigation from hose-reel raingun systems on field vegetable production in the UK and to evaluate the potential benefits of changing equipment and management strategies.

1.5. Aim and objectives

1.5.1. Research aim

This thesis aims to assess the impacts of raingun non-uniformity on field scale vegetable production and to evaluate a range of equipment and management strategies for improving irrigation efficiency.

1.5.2. Objectives

The key objectives are:

i) To develop an integrated modelling approach which can be used to evaluate the effect of a range of raingun equipment and management strategies on application uniformity and the consequent impacts on crop production;

ii) To review and assess the data requirements and suitability of potential raingun and crop models to fit the research framework;

iii) To conduct fieldwork to collect relevant soil, crop and irrigation data for model development and application;

iv) To calibrate, parameterise and validate appropriate raingun and crop models for use within the integrated modelling approach;

v) To investigate the impacts of a range of equipment and management strategies on raingun non-uniformity and crop yield and quality, and to evaluate the implications for the irrigated agriculture industry.

1.6. Research approach and dissertation structure

1.6.1. Research approaches

This research involved a combination of approaches including detailed literature review, an industry survey, fieldwork, computer modelling and discussions with key industry informants. Firstly, the issues relating to raingun non-uniformity were investigated, and the available raingun models evaluated and assessed for their suitability for this research. An extensive review of literature, in combination with an industry survey identified a suitable representative vegetable crop for study and its relevant features. Available crop yield models were then reviewed and evaluated to assess their suitability for the proposed research. Further industry consultation was then used to assist in the development of a crop quality model.

Two field sites were identified and established on two commercial vegetable farms in East Anglia in 2003 and 2004 to collect relevant soil, crop and irrigation data. These data were then used for the development, validation and application of the raingun and crop growth models. The impact of a range of equipment and management strategies on raingun irrigation uniformity and the consequences for crop production were then simulated and evaluated using an integrated modelling approach.

1.6.2. Dissertation structure

Chapter 1 outlines the background regarding water resources for irrigation in England and Wales, and the drive for improving irrigation efficiency. The research problem, aims and objectives are identified. A brief outline of the research approaches and dissertation structure is presented.

Chapter 2 presents the research framework for this thesis and outlines the rationale for developing an integrated modelling approach.

Chapter 3 reviews hose-reel raingun systems and the factors influencing raingun performance. A representative crop for the research is identified, and a comprehensive review of the crop and its irrigation is presented.

Chapter 4 identifies and describes the most suitable raingun irrigation simulation model for the research and describes and presents the field data required for modelling. The model is then parameterised and validated using relevant field data.

Chapter 5 identifies and describes the most suitable crop yield model for the research and describes and presents the field data required for modelling. The model is parameterised and validated using relevant field data.

Chapter 6 reviews crop quality research and presents a methodology for estimating the impact of non-uniform irrigation on crop quality. The model is validated using relevant field data.

Chapter 7 presents the results from the integrated modelling process in two stages: simulating the impact of a range of raingun equipment and management strategies on application uniformity; and simulating the impacts of non-uniform irrigation on crop yield and quality.

Chapter 8 evaluates the sensitivities, advantages and limitations of the integrated modelling process developed in this thesis; discusses the implications of the research findings for crop production, for demonstrating efficient irrigation and for the irrigated agriculture industry in general; develops recommendations to assist growers to improve irrigation efficiency; and suggests opportunities for further research.

Chapter 9 summarises the main conclusions of the research, with respect to the objectives identified in Chapter 1.

Chapter 10 provides the references used in the research.

2. Research framework

This chapter defines the proposed research framework for this thesis. The framework aims to provide an integrated approach to simulate and evaluate the impact of changing raingun equipment and management strategies on application uniformity and the consequences for crop production. The fundamental requirements of the framework to achieve the research aim and the use of a modelling approach are first outlined. The research framework is then presented and discussed.

2.1. Framework requirements and justification of approach

To achieve the research aim, the framework needs to address three main purposes:

i) To investigate the causes of raingun irrigation non-uniformity and the equipment and management strategies which growers might practically implement to reduce non-uniformity;

ii) To assess the impact of spatial and temporal heterogeneity in water application on crop yield and quality, and;

iii) To identify appropriate equipment and management strategies for minimising crop losses attributable to irrigation application.

By addressing these requirements, the research framework will provide important information to assist growers to reduce raingun non-uniformity and hence improve irrigation efficiency. This will help growers to improve crop yield and quality and will also assist them to demonstrate efficient irrigation both to fulfil grower protocol requirements and for abstraction licence renewal.

An entirely experimental approach to this subject area could only be conducted on a large and replicated scale over a number of years and would therefore not be feasible due to time and resource limitations. Consequently, a modelling approach integrating both raingun and crop growth simulation is proposed. However, in order to provide robust simulations and meaningful advice for growers, the models need to be parameterised and validated using relevant field data collected from a representative irrigated vegetable growing area in the UK.

2.2. Research framework

A research framework is proposed which focuses on the development of an integrated modelling approach that links existing models using data-bridging methods. The approach comprises two main components: raingun irrigation simulation and crop growth simulation (Figure 2.1). The outputs from these models can be used to evaluate the effects of raingun equipment and management strategies on application uniformity and the consequent impacts for crop production. The main elements of the research framework are described below.

2.2.1. Integrated modelling approach

Raingun irrigation simulation

Before any raingun irrigation simulation can be performed, the equipment and management strategies that affect raingun uniformity must first be examined, and those which are practically feasible for growers to alter identified (Chapter 3). This information will assist in identifying suitable raingun simulation models and their data requirements. Appropriate field data will then be collected and used to parameterise and validate the selected models (Chapter 4).

The raingun irrigation simulation component will comprise two elements: a wetted pattern simulation model and a field simulation model. The wetted pattern model will be used to generate a database of wind affected wetted patterns for a range of wind conditions and raingun parameters. The field simulation model will then select and overlap wetted patterns from this database according to ambient wind conditions and selected irrigation strategies to generate a map of spatially variable irrigation application depths in a simulated field (Chapter 4).

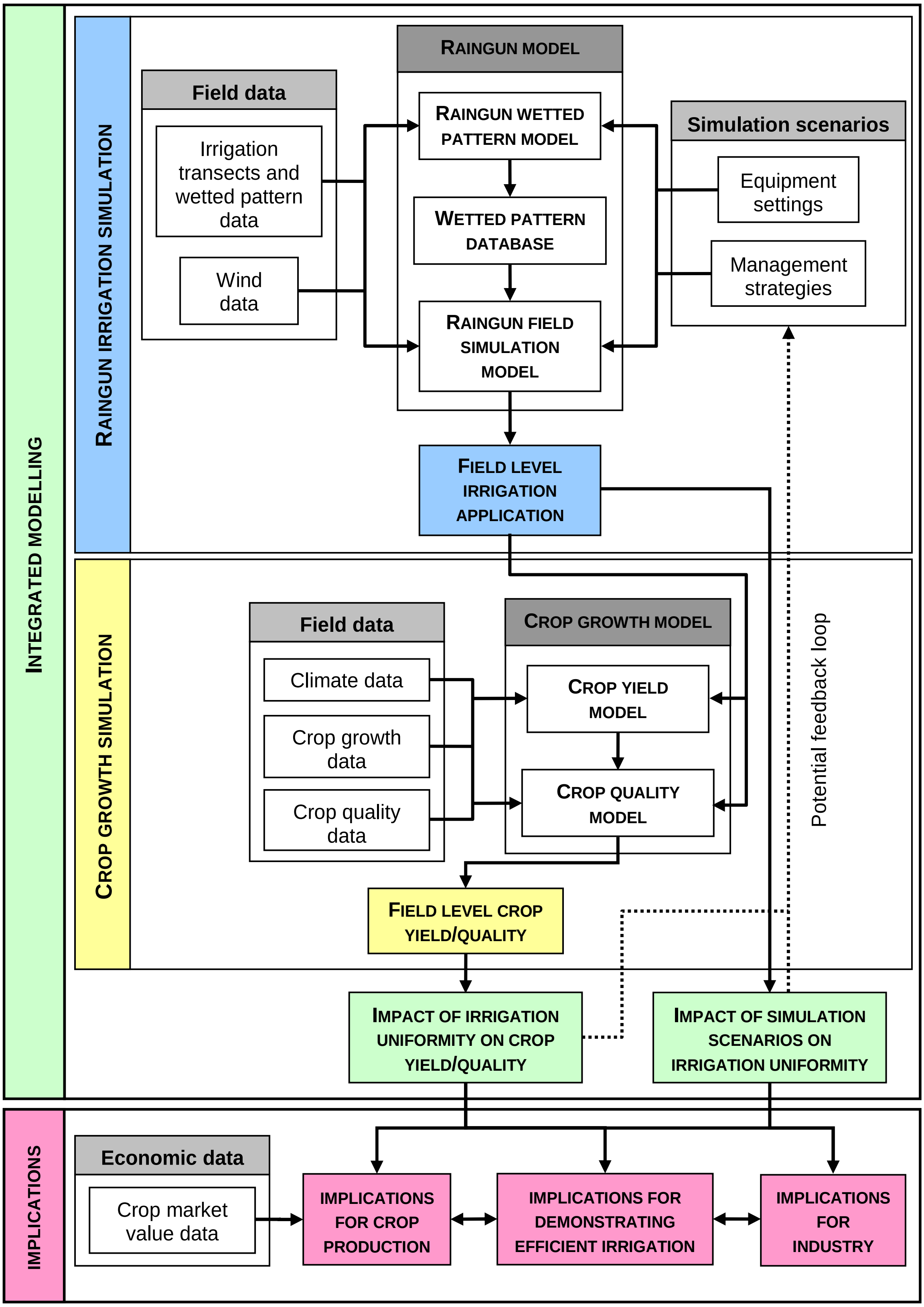

Figure 2.1 *Schematic representation of the proposed research framework for investigating and evaluating the impacts of raingun irrigation non-uniformity on crop production.*

Crop growth simulation

A representative crop must first be identified (from which inferences about other vegetable crops may be derived) and its response to irrigation investigated (Chapter 3). This information will be used to assist in identifying suitable crop growth models (including both yield and quality) and their data requirements. Appropriate field data will then be collected and used to parameterise and validate the selected crop growth models (Chapters 5 and 6).

The irrigation application patterns generated by the raingun simulation component will then be used as an input to the crop growth models. This will allow the simulation of crop yield and quality response to spatially and temporally heterogeneous irrigation application (Chapter 7).

2.2.2. Implications

The outputs from raingun modelling will allow investigation of the effect of changing equipment and management strategies on irrigation non-uniformity. The impact of the resulting heterogeneous irrigation applications on crop yield and quality can then be assessed using outputs from crop growth modelling. Together, these outputs will be used to evaluate the implications of the research for crop production, for demonstrating efficient irrigation and for the irrigated agriculture industry in general (Chapter 8). Findings from the integrated modelling process will also be used to develop recommendations to help growers to reduce raingun non-uniformity and hence improve irrigation efficiency (Chapter 8).

2.2.3. Similar research frameworks

A similar research framework has been used in a number of previous studies investigating the impact of irrigation non-uniformity on crop production. For example, Musa (1988) and Al-Naeem (1993) both used an analogous approach to link relatively simple raingun irrigation models and generic crop yield models calibrated for potatoes in the UK. A similar approach named NIWASAVE (NItrate and WAter SAVing) was developed by Cemagref (1999) as part of European Union (FAIR) funded research. This approach was used to model the effect of raingun irrigation non-uniformity on maize yields in France (Bruckler *et al.*, 2000; Lafolie *et al.,* 2000; Ruelle *et al.*, 2003) and wheat yields in the UK (Cemagref, 1999) and Mexico (Rodriguez *et al.*, 2004). The approaches used by these researchers compliment the research framework presented in this chapter.

3. Literature Review

This chapter provides an overview of hose-reel raingun irrigation systems and the characteristics and typical husbandry practices of a selected representative crop. The features and typical operational procedures of conventional hose-reel raingun systems in the UK are first described. This is followed by a review of the factors which affect system performance (i.e. application uniformity) and a summary of standard methods for evaluating raingun performance. The selection of a representative crop (carrots) for study in this research is then presented and justified. Finally, the relevant crop characteristics, typical husbandry practices and previous irrigation research relating to the crop are reviewed.

3.1. Hose-reel raingun irrigation

There are a variety of hose-reel raingun systems (sometimes known as hard-hose travellers or travelling guns) currently used in the UK. All commonly feature a high pressure rotating sprinkler (the raingun), borne on a wheeled carriage which is connected by a high density polyethylene hose to a large chassis-mounted rotating drum (the hose-reel) (Figure 3.1).

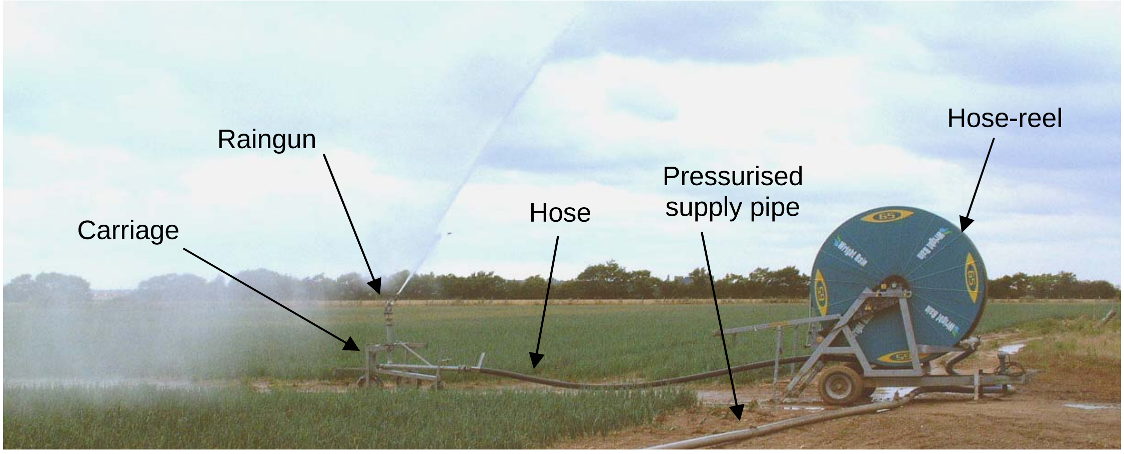

Figure 3.1 *A typical hose-reel raingun system in operation.*

To operate the system, the hose-reel is placed on the headland of a field (or sometimes in the centre of larger fields) and the raingun is towed slowly by tractor to the opposite end of the field, typically 200-500 m distant. In operation, the raingun emits water as a high pressure jet, rotating either 360° or, more usually, in a partial sector as the carriage is slowly pulled down the area to be irrigated by winding the hose onto the reel. This results in irrigation of a strip between 40 m and 100 m wide, depending on gun configuration and system pressure (Bailey, 1990). The process is repeated across the field, overlapping the irrigated areas to ensure adequate wetting (Figure 3.2). In this research, one single cycle of pulling the raingun down the field is termed a "pull", the spacing between pulls is referred to as the "lane spacing" and irrigating the whole field once is termed an "irrigation event".

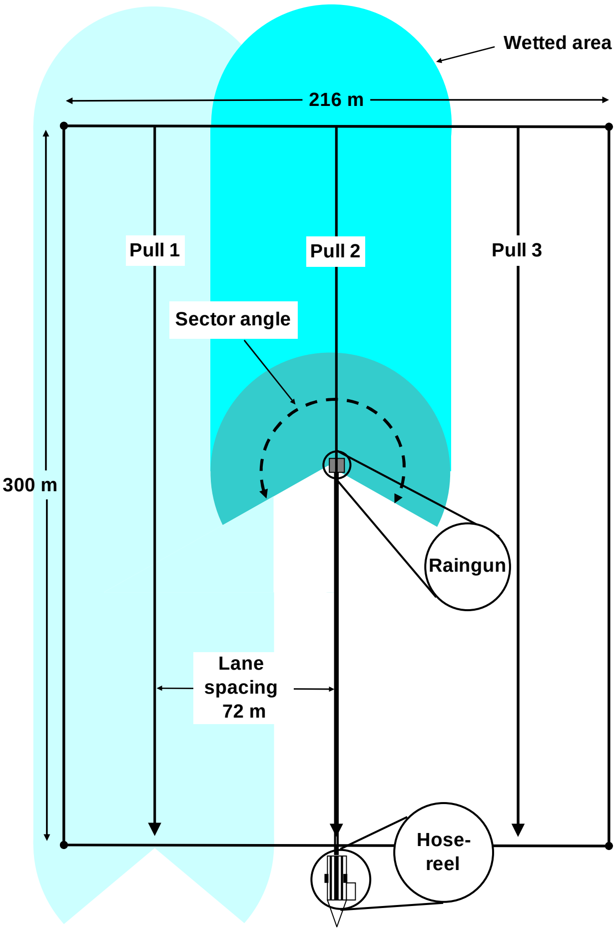

***Figure 3.2** Schematic plan view of typical hose-reel raingun irrigation, partway through an irrigation event.*

3.1.1. Hose-reel operation

On most modern systems, the supply water pressure provides power for winding the hose-reel via a turbine, although some older systems use pistons, bellows or a separate engine/tractor power take-off. The speed of a pull is typically controlled by automated valves on the turbine, allowing the user to program the appropriate speed for the depth of application required. Computer controlled turbine valves also provide some pressure compensation during speed control. Older mechanical control systems were notorious for uneven pull speeds and pressures as the hose was wound onto the reel (Rolland, 1982; Weatherhead *et al.*, 1987). However, computer control systems have considerably reduced these variations (Hipperson, 1985; Weatherhead *et al.*, 1987). Typically, irrigators aim to apply 25 mm per irrigation event, requiring a pull speed of 20-30 m h^{-1} for the most common gun configurations.

3.1.2. Raingun operation

There are a number of different rainguns commercially available in the UK, the most common of which are those manufactured by Nelson, Komet and Rainbird (in particular, the Nelson Big Gun SR150®[2]). All consist of a rotating barrel with nozzle mounted on a riser on the raingun carriage (Figure 3.3).

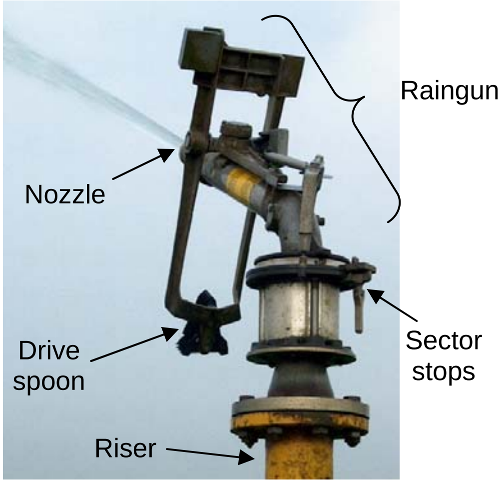

Figure 3.3 *Close up of a Nelson Big Gun SR150® raingun in operation.*

Gun rotation is usually controlled by a pivoting drive spoon which interrupts the water jet every few seconds, imparting a sideways force on the gun and causing rotation (Kay, 1983). This action also assists in breaking up the water jet to aid droplet dispersal. Rotation speed can be controlled by the angle of the drive spoon or a friction brake, and a full rotation usually takes two to five minutes (Kay, 1983). Where gun sectoring is required, manually adjustable sector stops are used to halt and invert the mechanism, causing the gun to rotate in the opposite direction. Some guns rotate using different methods (e.g. by turbine drives or a fast-return mechanism (Kay, 1983)), however these

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[2] Use of trade names does not imply endorsement by the author

have largely been superseded by the slow return models described above. Radio controlled variable sector angle guns are now available (e.g. Komet's Vector Control®) which allow growers to more effectively irrigate edges of fields or control the sector angle during a pull.

The angle of the raingun from horizontal (trajectory angle) is fixed on most gun models with the exception of the relatively new Komet Vari-Angle® and Nelson SRA150 Big Gun® models. A range of fixed angle guns are available to suit different purposes or wind conditions. However, for agricultural irrigation in the UK, an angle of 24° to horizontal is most commonly used.

Two nozzle types are available for rainguns – taper and ring nozzles. Ring nozzles break up the water jet more effectively than taper nozzles at the expense of reduced throw and greater wind distortion (Kay, 1983; Keller and Bleisner, 1990). Ring nozzles are generally used when irrigating crops with delicate canopies or on soils which are prone to capping. Taper nozzles are typically used for most other irrigation purposes. Nozzle diameters typically range from 12-50 mm; the most common in use in the UK are taper nozzles of 20-25 mm. Discharges from rainguns relate to nozzle size and operating pressure (typically 4-5 bar) and can range from 10-275 $m^3 h^{-1}$. For the Nelson Big Gun SR150®, fitted with a typical 25.4 mm taper nozzle and operating at 3.9 bar, the manufacturer's nominal flow rate is 50.1 $m^3 h^{-1}$ with an expected throw under still conditions of 48.9 m (NIC, 2006).

3.1.3. *Irrigation water supply systems*

On large farms (particularly those using groundwater or stored water resources), water is usually supplied through a buried high-pressure (8-12 bar) mains system with hydrants located on the margins/headlands of each field. Some systems operate with a single main hydrant per field; additional hydrants are provided by temporary over-ground pipes. A control system using, for example, variable speed pump technology maintains the appropriate pressure and flow rate through the mains depending on demand. Smaller enterprises often use mobile diesel or tractor powered pump sets at each individual hose-reel, sourcing water from irrigation ditches or surface streams adjacent to the irrigated area.

3.2. Factors affecting raingun performance

Turker (1998) identified three factors which affect raingun or sprinkler[3] performance: design characteristics, operational procedures and climatic conditions. Design characteristics are predominantly fixed and are related to the patterns generated by the intrinsic raingun features. These include: raingun make and model, riser head, nozzle size and type, and equipment maintenance. Operational procedures are features which are potentially adjustable in the course of an irrigation event. These include: system pressure, pull speed, lane spacing, trajectory angle, sector angle and rotation speed. Climatic conditions refer primarily to wind speed and wind direction, but also to factors which influence evaporation losses. Although there is some obvious overlap between topics, they are discussed separately below.

3.2.1. Design characteristics

Make and model

Differences in raingun barrel and drive spoon designs can influence water jet break-up with consequent effects on throw, wind susceptibility and spatial application. However, it appears that no research has been carried out to examine the application uniformity of different raingun designs.

Riser head

The riser head affects the height of the raingun nozzle from the surface, which influences the throw and exposure of the water jet to wind (Heerman *et al.*, 1983). For example, Nderitu and Hills (1993) found that lowering the riser height in solid set and set-move sprinklers adversely affected application uniformity.

Nozzle size and type

Apart from manufacturer's information on wetted area coverage, limited work has been carried out on the effect of raingun nozzle type and size on application uniformity. In large-scale raingun irrigation of sugarcane, Smith *et al.* (2002) found that taper nozzles gave superior performance over ring nozzles. However, as noted in Section 3.1, ring

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[3] Rainguns and sprinklers share many operating characteristics due to similar design features

nozzles are more suitable for delicate crop types and soils. Consequently, nozzle choice tends to be a compromise between these issues.

Equipment maintenance

The deleterious effect of poor maintenance on application uniformity was demonstrated in sprinkler irrigation by Louie and Selker (2000), and it seems reasonable to assume that similar issues would occur with rainguns. Indeed, observations during fieldwork in 2003 during this research showed that a faulty drive spoon mechanism considerably reduced application uniformity.

3.2.2. Operational procedures

Water pressure

Incorrect water pressure at the nozzle can have considerable impacts on the application uniformity of rainguns (Turker, 1998; Millar, 2002). Low pressure (typically <3.5 bar for common UK raingun systems) reduces throw distance and results in poor jet break-up and large droplets which can potentially damage crops and soil. As a result, high water deposition tends to occur near the outer perimeter of the wetted pattern, adversely affecting uniformity. Conversely, high water pressures (typically >5 bar) cause excessive jet break-up and fine droplets which are prone to wind-drift. In this case, high water deposition tends to occur near the gun, also resulting in low uniformity. (Kay, 1983; Heerman *et al.*, 1983). Some researchers (e.g. Weatherhead *et al.*, 1987) suggest that controlled variations in raingun pressure could be used to improve uniformity under windy conditions. However, no research on this subject appears to have been carried out.

Pressure variations during raingun operation with modern pressure compensating turbines are relatively low compared to older systems (Rolland, 1982; Hipperson, 1985; also see Section 4.3.5). This has largely eliminated pressure-related uniformity variation during a raingun pull for most systems in use in the UK. However, the water supply pressure to rainguns has been found to be sub-optimal in over three-quarters of rainguns, primarily as a result of pumping and conveyance systems which are poorly matched to the irrigation system demands (Millar, 2002). Revision of system design and/or changes in irrigation management to reduce peak demands could help to ensure adequate water pressure to minimise pressure-related application uniformity issues.

Pull speed

The raingun carriage should be pulled down the field at a constant speed to maintain application rates and achieve high application uniformity (Addink *et al.*, 1983; James, 1988). As noted in Section 3.1.1, early systems had poor speed control, but the widespread use of computer controlled turbine valves has largely resolved this issue (Hipperson, 1985; Weatherhead *et al.*, 1987).

Lane spacing

Travel lane spacing is critical to achieving uniform application between overlapping pulls. The industry standard spacing in the UK is typically 72 m, although field observations during this research suggested that spacing actually varies from about 60 m to 75 m, often changing between irrigation events. Indeed, Augier (1996) reported that 65% of travelling guns in France operated with incorrect lane spacings.

Many researchers (e.g. Schull and Dylla, 1976a,b; Oakes and Rochester, 1981; Musa, 1988; Al-Naeem, 1993; Grose, 1999) have modelled raingun operation under a variety of wind conditions and have suggested lane spacings to suit their studied systems. Most authors acknowledge that no single lane spacing gives high uniformity under all wind conditions. In general, lane spacings are recommended to be 80% of the wetted diameter under zero wind conditions, 70% for wind speeds of 0-2.5 m s^{-1}, 60% for 2.5-5 m s^{-1} and 50% for >5 m s^{-1} (Rolland, 1982; Kay, 1983) (see Appendix A for wind speed conversions between m s^{-1}, km h^{-1} and mph). However, changing lane spacing to suit conditions presents practical problems for growers. Many operations have fixed hydrants from the buried mains system at or near the industry standard spacing in their fields and may be unwilling to use temporary pipes systems to supply water to an ever-changing lane spacing set-up. More importantly, by altering lane spacing, additional full or partial pulls may be required to irrigate a field. This could result in increased irrigation costs and would complicate planning of irrigation equipment rotation.

Trajectory angle

Raingun trajectory angle can play an important role in application uniformity since it influences the wetted pattern and the height which water droplets attain. This affects the droplet exposure time to wind (Solomon, 1990) and the wind intensity experienced (since wind speeds generally increase with height – Heerman *et al.*, 1983). Heerman *et al.* (1983) and von Bernuth (1988) suggest that high trajectory angles of about 29° to 32° tend to provide the best uniformity under still conditions, but should be decreased with increasing wind speeds to as low as 5°. Similarly, research by Al-Naeem (1993) indicated that low trajectory angles produced more uniform application under high winds and *vice versa*. However, Al-Naeem (1993) concluded that there was no single optimal trajectory angle for all wind conditions. Pullen (2006) reported that by using a Komet Vari-Angle® gun high application uniformities could be achieved with a trajectory angle of 15° at high wind speeds and 25° at low wind speeds. However, using low trajectory angles risks crop and soil damage from the impact of droplets which have failed to lose sufficient energy in transit (Keller and Bleisner, 1990). Therefore, most guidelines suggest that for typical wind conditions, a trajectory angle of 23° to 25° is most suitable, hence most fixed angle rainguns used in the UK operate at 24°. Research by Turker (1998) indicated that automated sprinkler trajectory and sector angle adjustments could reduce wind distortion of wetted patterns by up to 40%. However, such technology for rainguns has yet to be developed and tested under field conditions before it can be considered for commercial purposes.

Sector angle

Changing the sector angle affects the application pattern (and rate) as the raingun moves down the travel lane. Keller and Bleisner (1990) suggested that under still conditions, a sector angle of between 210° and 240° would give the optimal uniformity for a single pull and would also result in optimal uniformity for overlapping pulls. Similarly, Grose (1999) suggested that a sector angle of 236° provided optimal uniformity for a single raingun pull and Growcom (2004a) advise a sector angle of 240° to 270°. Al-Naeem (1993) demonstrated that for narrow lane spacings (<64 m) and low wind speeds, gun rotations close to 180° or 360° provided the greatest uniformity, but at wider spacing and higher wind speeds, 210° to 270° sector angles were optimal. Choice of sector angle in the UK seems to loosely conform to this consensus, but is also influenced by the irrigator's estimates of sector angle requirement for irrigating the start and end of a pull. It is apparent, though, that sector angles are largely ignored (Swallow, 2001), and the positions of sector stops (which can move during use or transit) are generally unchecked. Radio controlled adjustment of sector angle is now possible with some gun models (e.g. Komet's Vector Control®) which may allow operators to change sector angles to suit wind conditions. Automated sector angle adjustment on sprinklers has been shown by Turker (1998) to reduce wetted pattern distortion. However, such technology for rainguns has yet to be developed and tested under field conditions before it can be considered for commercial purposes.

Rotation speed

The rotational speed of a raingun head can also have an impact on application uniformity. When stationary, the high-speed water jet from a raingun nozzle entrains the surrounding air at a velocity approaching that of the jet. However, when the jet position changes rapidly, it encounters slower moving air which provides extra resistance to the water. This increases jet break-up which in turn makes the application pattern more susceptible to wind distortion (Solomon, 1990; Finkel, 1982; Bilanski and Kidder, 1958). There appears to have been no research carried out to examine the effect that raingun rotation speed has on application uniformity.

3.2.3. Climatic conditions

Wind speed and direction

Many researchers have investigated the effect which wind has on overhead sprinklers in general and rainguns in particular (e.g. Schull and Dylla, 1976a,b; Oakes and Rochester, 1981; Arshad Ali and Barefoot, 1984; Dalvand, 1986; Musa, 1988; Seginer *et al.*, 1991; Richards and Weatherhead, 1993; Al-Naeem, 1993; Grose, 1999; Tarjuelo *et al., 1999*). Through observation and simulation, these authors have surmised that the general wind effects are: a considerable range shortening upwind; a small range elongation downwind; and a considerable narrowing of the wetted pattern perpendicular to wind direction. This consequently decreases the wetted area and increases deposition rates, particularly in the areas to the side of the sprinkler perpendicular to the wind direction and a little downwind. The narrowing of the wetted pattern perpendicular to wind has led researchers to conclude that wind direction in addition to wind speed is also important to application uniformity. In general, winds blowing parallel to the travel direction result in a lower uniformity than those blowing perpendicularly. Consequently, when designing raingun irrigation systems, growers are advised to ensure that the travel lanes run perpendicularly to the prevailing wind direction (e.g. Schull and Dylla, 1976a,b; NIC, 1999; Growcom, 2004b).

Considerable distortion of the application pattern can occur even at relatively low wind speeds (<3 m s^{-1}) which has led to advice for raingun users not to irrigate where wind speeds exceed 4-5 m s^{-1} (e.g. Schull and Dylla, 1976a,b; Growcom, 2004b). However, in reality, this is often impracticable for growers, due to crop irrigation needs and equipment constraints. It is generally considered by growers to be better to risk non-uniform irrigation in windy conditions than to not irrigate at all. One option commonly suggested to growers is to irrigate at night when wind speeds in most areas are on average half the day time speeds (e.g. Bailey, 1987; Millar, 2002; Growcom, 2004b). However, during dry spells when irrigation demand is at its peak, many growers already irrigate through both the day and night in order to complete irrigation schedules.

Spray evaporation

Increases in wind speed and temperature and decreases in relative humidity and droplet size will increase spray evaporation rates (Yazar, 1984). Estimates for evaporative losses from sprinklers range from 2%-17% (Yazar, 1984; Kincaid and Longley, 1989; Lorenzini, 2002), predominantly at the lower end of the range. Indeed, Heerman *et al.* (1983) suggest that losses are generally only 1-2% of discharged water. This is most likely due to the fact that above a droplet size of 1.5-2 mm, evaporative losses are virtually negligible (e.g. Edling, 1985; Kohl *et al.*, 1987; Kincaid and Longley, 1989). Practices which promote jet break-up into fine droplets (e.g. using ring nozzles or excessively high gun pressures) will therefore tend to increase evaporative losses. Although evaporation rates are not likely to greatly influence application uniformity during a single irrigation pull, daily and diurnal differences in wind speed, temperature and relative humidity may affect evaporation rates and hence application depths between pulls carried out on different days or at different times. Consequently, to reduce evaporative losses, growers may benefit from irrigating at night when wind speeds and temperatures are generally lower and relative humidity higher than during the day (Bailey, 1987).

3.2.4. Summary

Without investing in new technology, the options available to growers to reduce the non-uniformity of raingun irrigation are limited to ensuring adequate equipment maintenance, supplying the correct water pressure and using an appropriate lane spacing and orientation, trajectory angle, sector angle, rotation speed and time of irrigation (day/night). Of these eight strategies, it can be assumed that equipment maintenance, the correct water supply pressure and rotation speed are relatively straightforward to resolve without further study. However, the impact of lane spacing and orientation, trajectory angle, sector angle and time of irrigation on raingun non-uniformity and the consequences for crop yield and quality require further investigation. These parameters therefore form the focus of this study.

3.3. Evaluating raingun performance

There are a number of measures for evaluating the uniformity of irrigation, of which the most widely accepted are the Christiansen's coefficient of uniformity (CU) (Christiansen, 1941) and the distribution uniformity (DU) (Criddle *et al.*, 1956).

The Christiansen's coefficient of uniformity (Christiansen, 1941) gives an average measure of the irrigation uniformity over an area; it does not indicate the magnitude of localised non-uniformity. The measurement penalises both under- and over-irrigation relative to the magnitude of the difference from the mean application (Zoldoske and Solomon, 1988). CU is calculated using Equation 3.1:

$$CU\% = 100\left(1- \frac{\sum X}{nm}\right)$$

Equation 3.1

where CU% = Christiansen's coefficient of uniformity expressed as a percentage; X = absolute deviations of observed depths from the mean value (mm); n = number of observations; and m = mean of observed depths (mm).

The distribution uniformity (Criddle *et al.*, 1956) emphasises under-watered areas and provides a measure of the magnitude of localised water shortage. DU is calculated as the ratio of the mean application in the lowest quarter of the data to the overall mean application using Equation 3.2:

$$DU\% = 100\left(\frac{m_{lq}}{m}\right)$$

Equation 3.2

where DU% = distribution uniformity expressed as a percentage; m = mean of observed depths (mm); and m_{lq} = mean of lowest quarter of the application data.

Typically, overhead irrigation systems are regarded as having low uniformity when CU <75% or DU <60%. Conversely, a CU of >85% or DU >75% indicates a relatively high uniformity (Keller and Bleisner, 1990). No irrigation system is likely to achieve 100% CU or DU, although carefully managed systems can approach 95%. Kruse *et al.* (1990) suggest that spray irrigation systems should be designed to achieve a CU of 80%, and a well managed system could achieve 90% under favourable wind conditions.

3.4. Representative crop selection

This section identifies a representative crop for crop growth modelling from which results could be transferred to other vegetable crops. The selected crop must be important within the horticultural industry in its own right; be typically irrigated using hose-reel rainguns; be responsive to irrigation; have a suitable morphology for study and be grown in an accessible area for study.

In the UK field vegetable sector, over 50% of the 123,527 ha grown in 2004/5 was comprised of four crops - green peas, dried peas, cauliflower and carrots, with green peas accounting for more than a quarter of the total area (Figure 3.4). However, in terms of market value, carrots were the most important crop, equating to over £128 million in 2004/5 or £13,000 ha^{-1} (DEFRA, 2005b), equivalent to nearly one fifth of the total vegetable market value.

Carrots are predominantly grown in light soils in the east and south east of the UK, particularly in East Anglia. The crop is generally considered to be responsive to irrigation with estimates of yield increase ranging between 0.03 and 0.31 t ha^{-1} mm^{-1} (MAFF, 1981; Groves and Bailey, 1994; Morris *et al.*, 1997). However, irrigation is not only important for carrot yield, but also plays a crucial role in root quality. Therefore, in order to secure reliable yields and quality, UK grown carrots are almost all exclusively irrigated (although a few growers in the west of the mainland where rainfall is higher do not irrigate). Industry estimates from a survey of agronomists conducted for this study suggest that hose-reel rainguns accounted for between 60% and 90% of the irrigation systems used for carrots.

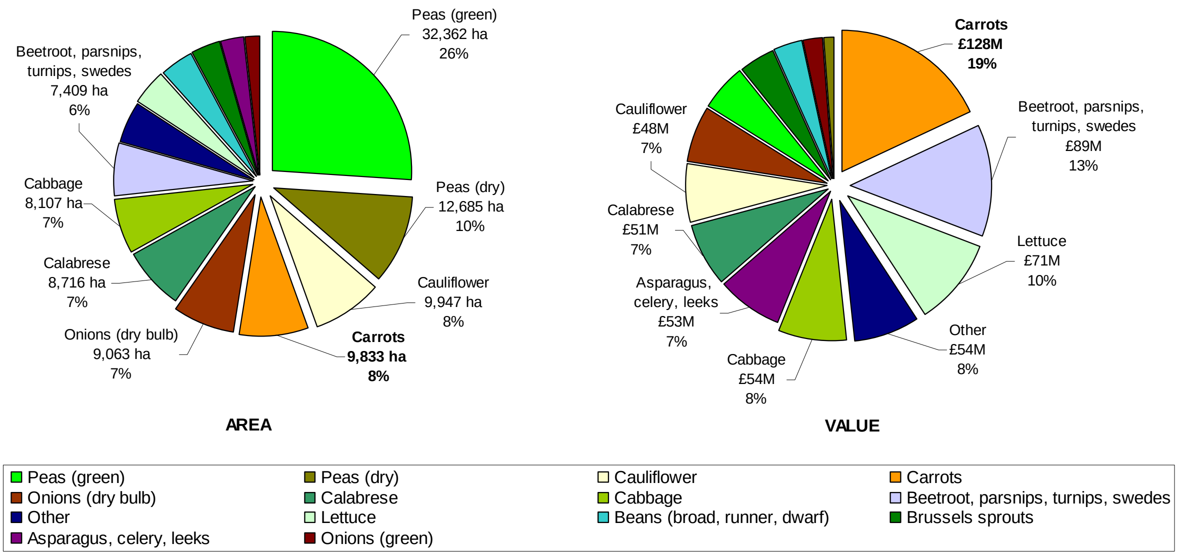


***Figure 3.4** Reported UK field vegetable areas for 2004/5 and market values for 2004 by crop type (DEFRA, 2005b).*

Finally, carrot morphology is useful for study purposes, as it has a distinct harvested part (tap root) rather than a more ill-defined vegetative harvested part such as in most brassica crops or lettuce. Carrots were therefore chosen as the representative crop to investigate the impacts of irrigation heterogeneity on crop yield and quality in this study. The findings relating to this crop would also be applicable to other similar field vegetable crops such as parsnip and perhaps also beetroot and sugar beet. The implications of the research should also have some relevance to other raingun irrigated crops (e.g. other field scale vegetables and potatoes).

Two commercial carrot growers in East Anglia were identified through the Horticultural Development Council who were known to irrigate using hose-reel rainguns and were keen to participate in this research – Tompsett Burgess Growers Ltd. at Isleham, Ely and W.O. and P.O Jolly Ltd. at Roudham, Thetford. Both sites were readily accessible in terms of travel distance, so were ideal for fieldwork and study purposes.

3.5. Carrots

3.5.1. Botany, development and growth

Carrots (*Daucus carota* L.) are members of the *Apiaceae* botanical family (previously *Umbelliferae*), characterised mainly by their up-turned umbrella shaped inflorescence (compound umbel) (Rubatzky *et al.*, 1999). The carrot is biennial, forming a rosette of double compound leaves and a fleshy tap-root with many fibrous roots in the first year. It is this storage root which is harvested in the first year for consumption (Nonnecke, 1989, Benjamin *et al.*, 1997). If permitted to develop into the second year of its life-cycle, the storage root provides the energy required for inflorescence.

Figure 3.5 illustrates the typical development of a carrot crop in the UK based on Doorenbos and Pruitt (1984) and Allen *et al.* (1998) and modified for the UK based on industry advice (Martin, *pers. comm.* 2005; Wright, *pers. comm.* 2005; Will, *pers. comm.* 2005). It should be noted that there are likely to be significant developmental differences due to variety, climate, soil conditions, husbandry and sowing date.

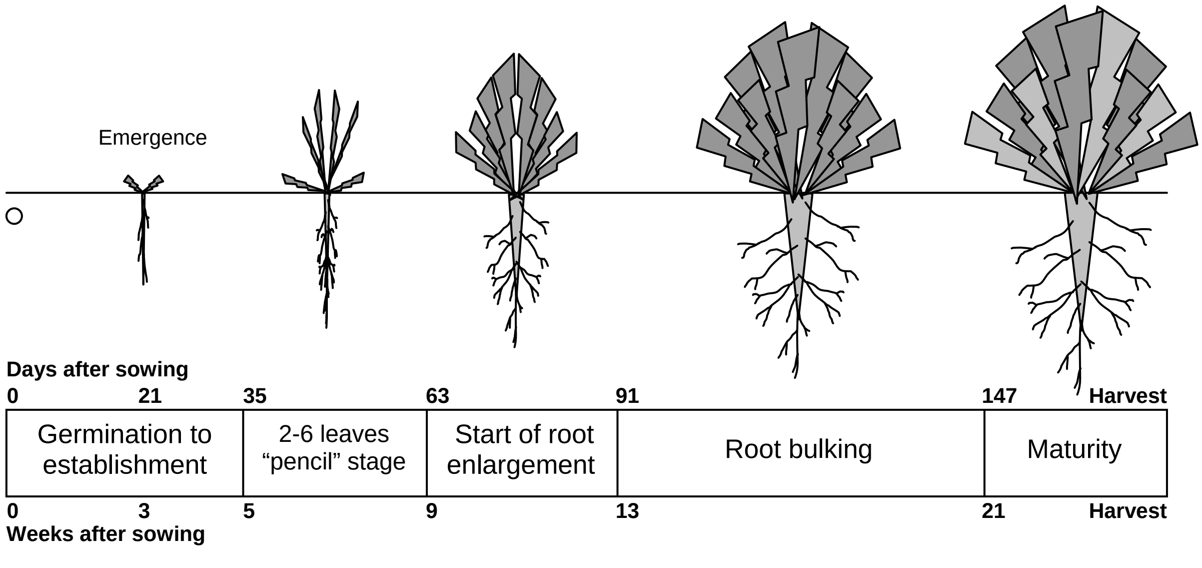


***Figure 3.5** Typical developmental stages of a carrot crop in the UK.*

Typical of the *Apiaceae* family, carrots are relatively slow to germinate and establish, requiring some 1-3 weeks for emergence and up to 4 weeks for true leaf development (Rubatzky and Yamaguchi, 1997; Kotecha *et al.*, 1998; Rubatzky *et al.*, 1999). After the

2-6 leaf stage, the crop undergoes rapid canopy expansion and storage root enlargement. Foliage and storage root growth are closely connected although the canopy tends to reach its full potential near mid-season whereas storage root growth (bulking) continues until “maturity” (harvest) (Rubatzky *et al.*, 1999). Figure 3.6 illustrates canopy growth (leaf area index) and storage root growth through the season for variety Sixpak (a fresh market variety) grown in Quebec, Canada (Bourgeois and Gagnon, 2001).

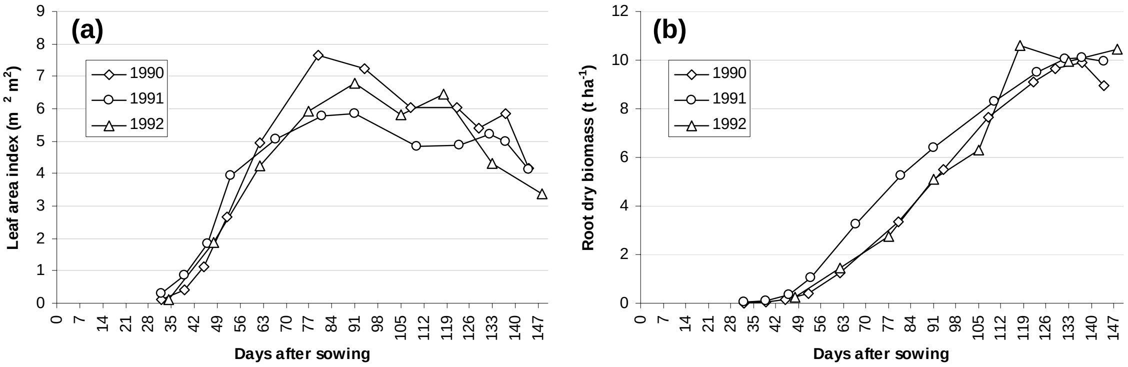


Figure 3.6 *Seasonal leaf area index expansion (a) and root dry biomass growth (b) of variety Sixpak grown in Quebec, Canada (Bourgeois and Gagnon, 2001).*

Carrots can typically exploit water to a depth of 0.75-1 m (Bailey, 1990; Rubatzky and Yamaguchi, 1997; Rubatzky *et al.*, 1999; Thorup-Kristen *et al.*, 2001), although Borg and Grimes (1986) suggest that roots can extend to 3 m under favourable conditions. Despite a deep rooting system, the majority of the fibrous roots tend to occur within the most friable upper 0.3 m of soil (Rubatzky *et al.*, 1999). Early root growth is rapid, achieving depths of up to 0.2 m within 24 days of germination in experiments controlled at 16°C (White and Strandberg, 1978). Pope (*pers. comm.,* 2003) confirmed that similarly rapid root expansion also occurs within the early stages of carrot crop development in the UK.

There are many carrot cultivars available which provide growers with a choice of size, shape, colour, taste, texture, root smoothness, hardiness, handling robustness etc. to suit the different market sectors (e.g. fresh loose or pre-pack, cut and peel or processing). The National Institute for Agricultural Botany (NIAB) has produced a comprehensive guide to the varieties available in the UK and their properties (NIAB, 2000). The dominant variety in the UK is Nairobi, with 70-80% of the market share (Hipperson, *pers. comm.* 2005; Wright, *pers. comm.* 2005; Will, *pers. comm.* 2005; Birkenshaw, *pers. comm.* 2005; Rickard, *pers. comm.* 2005). Nairobi is a Nantes type carrot that has roots which are almost cylindrical with a blunt apex and tends to provide a majority of roots with a shoulder diameter of 20 mm to 45 mm and a length of 100 mm to 180 mm. It can be grown throughout the year on most soils (although not as successfully on peat) for supply to both the fresh and processing sectors (NIAB, 2000). Typically it yields upwards of 100 t ha^{-1} and on ideal sites as much as 160 t ha^{-1}.

3.5.2. Crop husbandry

Carrots may be sown in the UK from October to July to secure an almost year-round supply. Those being overwintered (so called “earlies”) must be protected with polythene to prevent frost damage. “Early maincrop” carrots are those sown from March onwards for harvest in September to November. “Late maincrop” varieties tend to be sown later in the spring for harvest in late winter or early spring. To prevent frost damage during winter, the roots are stored in-situ either before or after foliage removal and are covered with straw (Hardy and Watson, 1982; MacCarthy, 1989; Finch *et al.*, 2002). As an alternative to field storage over winter, carrots may be stored in purpose-built cold rooms, although this practice is not widespread in the UK.

Correct preparation of the seedbed is crucial to the production of quality carrots since any obstructions to growth will result in reduced yield and misshapen and/or forked roots with little market value. Subsoiling may be necessary if compaction or pan-formation is suspected, stones should be removed and the soil should be worked to a fine tilth (White, 1978; Strandberg and White, 1979; Rubatzky and Yamaguchi, 1997; Nonnecke, 1989; Finch *et al.*, 2002). Consequently, in the UK, carrots tend to be grown on light soils with few stones such as sandy silt loams, sandy loams, loamy sands, sand and fenland peats (Hipperson, *pers. comm.* 2005; Wright, *pers. comm.* 2005; Will, *pers. comm.* 2005; Birkenshaw, *pers. comm.* 2005; Rickard, *pers. comm.* 2005). Initial soil working operations (not including bed formation) should be completed by February or March for an April sowing of maincrop carrots (Hardy and Watson, 1982).

Most commercial growers operate a bed system of varying dimensions depending on crop end-use and equipment constraints. In general, carrots are sown in bands 100 mm to 200 mm apart within a bed of up to 1.6 m wide which is often raised by 100 mm to

300 mm (Hardy and Watson, 1982; Rubatsky *et al.*, 1999). The predominant system used in the UK is four triple rows of carrots sown in slight depressions in a raised bed on 2 m wheel centres (Figure 5.11 and Figure 7.2) (Will, *pers. comm.* 2005).

Sowing density is critical to reduce heterogeneity, maximise yields and minimise growing time. Workers such as Robinson (1969), Currah and Barnes (1979), Mack (1980), McCollum *et al.* (1986), Li *et al.* (1996) and Lazcano *et al.* (1998) have done much to determine optimal sowing densities. In particular, it is necessary to increase the sowing density on the edge of a band by up to 100% to prevent these rows achieving greater size than the inner rows where competition hinders growth (Hardy and Watson, 1982; Benjamin and Sutherland, 1992; Benjamin and Reader, 1998). Consequently, high-precision drilling with specially coated, free-flowing seed is necessary to achieve high marketable yields.

Weed control is particularly important during the early growth stages of carrot due to the crop's relatively poor competitiveness as a result of slow early growth (Rubatzky and Yamaguchi, 1997; Kotecha *et al.*, 1998). Therefore stale seedbed techniques and a relatively intensive pre-drilling, pre-emergence and early post-emergence herbicide regime are typically used to attain good establishment (Hardy and Watson, 1982).

Pest and disease control primarily focuses on carrot root fly (*Psilla rosae*) which can cause total crop loss if untreated. The main generation of fly occurs in late May and June, but a second generation also occurs from July to September, with an occasional outbreak in November (Hardy and Watson, 1982). There are many effective insecticides available for carrot root fly which can be used in conjunction with the national pest forecasting services such as that run by ADAS. Other notable pests include nematodes, cutworms and aphids (Ellis and Hardman, 1992). Important carrot diseases are mainly soil-borne and include cavity spot, scab, sclerotinia and violet root rot (Dixon, 1981; Groves and Bailey, 1994; Pettitt and Gladders, 2003; HDC, 2005). Soil-borne pathogens tend to be controlled by pesticides and long rotations between root crops (usually 5-7 years with cereals, potatoes or other vegetables) (Hardy and Watson, 1982; Finch *et al.*, 2002; Wright, *pers. comm.* 2003). Carrots are also affected by leaf diseases including alternaria and powdery mildew which are typically controlled by fungicide applications

(Thomas and Martin, 2002; ADAS, 2003; HDC, 2005). The effect of irrigation on the incidence of carrot diseases and other disorders is discussed in Chapter 6.

Carrot crops have a moderate to high nutritive requirement, typically requiring 75-150 kg ha^{-1} nitrogen, 25-125 kg ha^{-1} phosphorous and 0-175 kg ha^{-1} potassium as a base application supplemented by a further 75-150 kg ha^{-1} nitrogen through the season (Rubatzky *et al.*, 1999). High soil nitrogen levels can, however, lead to excessively vigorous canopy growth at the expense of root growth (Wright, *pers. comm.* 2004). Carrots are also sensitive to deficiencies in the trace elements boron, copper and manganese (Hardy and Watson, 1982).

The crop has a relatively high water demand of 450-600 mm per season to achieve good yields (Rubatzky and Yamaguchi, 1997). Industry estimates suggest that carrot daily water use in the UK rises to a maximum of approximately 5 mm d^{-1} at full canopy cover in high evapotranspiration conditions before falling to 2.5-3 mm d^{-1} near harvest (Wright, *pers. comm.* 2005; Martin, *pers. comm.* 2005). In addition to yield, water also plays a significant role in carrot quality, influencing crop establishment and uniformity, shape, size, appearance, taste and texture (Mazza, 1989; Will, *pers. comm.* 2005 – see Chapter 6). In the major carrot growing areas (primarily eastern England), rainfall over the main carrot season (April – October) rarely exceeds 360 mm (Smith, 1976). Therefore supplementary irrigation is required in virtually all years on the light soils typically used for carrot production.

Irrigation scheduling methods vary widely between growers. Many growers (particularly smaller enterprises) tend to use simple visual assessments of crop and soil condition to schedule irrigations, often fitting carrot irrigation around more important crops such as potatoes and salads when equipment is limited. However, it is widely considered that the use of more accurate scheduling methods is increasing in the vegetable industry, particularly on larger enterprises. Among the more popular of these methods are soil moisture monitoring using a range of equipment types (which is typically contracted out to specialists) and water balances using evapotranspiration and rainfall data obtained either from nearby weather stations or from rain and evapotranspiration gauges. A typical irrigation schedule for maincrop carrots is presented in Table 7.3.

Industry estimates from a survey of agronomists for this study indicated that 60-90% of irrigated carrots are irrigated using hose-reel rainguns (Will, *pers. comm.* 2005; Hipperson, *pers. comm.* 2005; Wright; *pers. comm.* 2005; Birkenshaw, *pers. comm.* 2005; Rickard, *pers. comm.* 2005). The remainder are irrigated using hose-reels fitted with booms, linear moves, sprinklers and centre pivots.

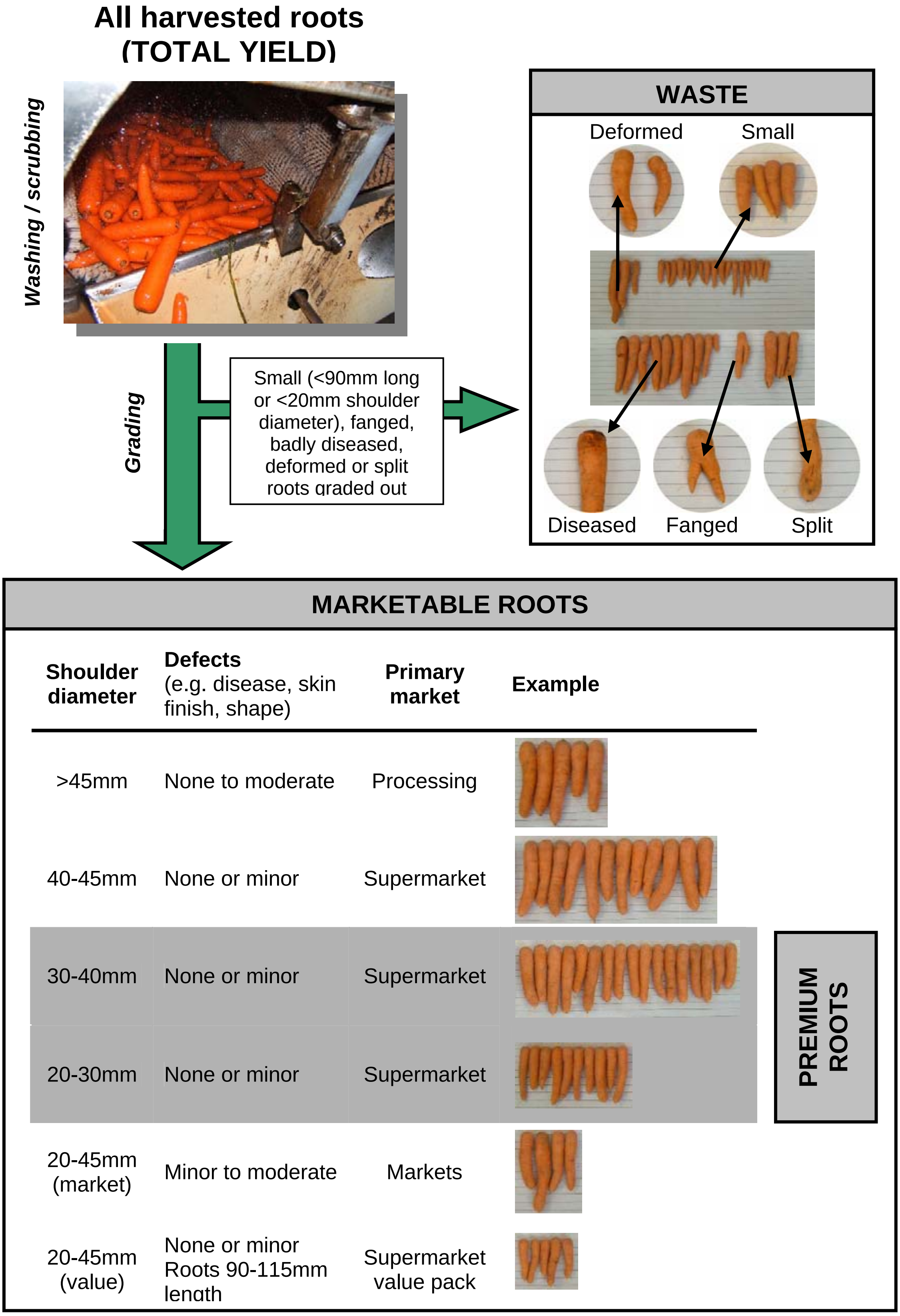
3.5.3. Carrot production and markets in the UK

Carrots form an important part of irrigated horticulture in the UK with an area of between 8,100 and 13,700 hectares grown annually from 1994-2004 (DEFRA, 2005b). In this period, the area of carrots grown was the third or fourth largest of all the field vegetable crops (e.g. Figure 3.4). Approximately three-quarters of the total area in 2004/5 was grown in England and Wales, predominantly in East Anglia, Lincolnshire and Nottinghamshire (DEFRA, 2006b; Hipperson, *pers. comm.* 2005; Wright, *pers. comm.* 2005; Birkenshaw, *pers. comm.* 2005; Rickard, *pers. comm.* 2005; Will, *pers. comm.* 2005). The total UK annual carrot production for 1994-2004 was between 512,000 and 760,000 tonnes, with a market value estimated to be between £67 and £163 million or £5,800-£16,800 per hectare (DEFRA, 2005b).

Approximately 80% of the UK crop is sold under contract to multiple retailers (often through a packing or processing company) and is therefore subject to stringent quality controls on size, shape, smoothness, colour, splitting and pest damage (ADAS, 2003). On top of these quality demands, supermarkets place their own criteria in contracts with growers, often including requirements for reliable supply of carrots and assurances of the environmental sustainability of crop production.

As a result of the stringent quality requirements, only 50-70% of a carrot crop is typically considered “marketable”, with premium quality carrots comprising 20-50% of the total harvested crop. However, the grading process often varies considerably between different packers and processors, primarily as a result of the quality criteria required by their markets. Typically, grower contracts with processors and packers are either indirectly or directly linked with marketable yields, putting further pressure on growers to maximise not only crop yields, but more importantly, crop quality. An illustration of the grading process typically used by the packing and processing industry (including the definition of marketable and premium roots used in this study) is given in Figure 3.7.

The harvested crop is first washed (and sometimes scrubbed or abraded to remove minor skin defects) before waste roots (i.e. under-size, fanged and badly diseased, deformed or split roots) are removed by hand and/or automated grading machines. The roots left after this process are termed the “marketable yield” in this study (sometimes known as the “packable roots” or “pack out”). The marketable roots are then graded according to shoulder diameter and quality criteria depending on the end market. Roots with little or no defects and a shoulder diameter of 20-40 mm are typically destined for supermarkets (defined here as “premium roots”). The waste roots are typically used for animal fodder (or occasionally for processing) at a significantly reduced or zero price (Birkenshaw, 1990; Pope, *pers. comm.* 2003).



Shoulder diameter	Defects (e.g. disease, skin finish, shape)	Primary market	Example
>45mm	None to moderate	Processing	
40-45mm	None or minor	Supermarket	
30-40mm	None or minor	Supermarket	
20-30mm	None or minor	Supermarket	
20-45mm (market)	Minor to moderate	Markets	
20-45mm (value)	None or minor Roots 90-115mm length	Supermarket value pack	

Figure 3.7 *Illustration of a typical carrot industry grading process including the definition of marketable and premium roots.*

3.5.4. Carrot related irrigation research

A considerable amount of international research has been carried out on carrot irrigation, the majority focussing on defining optimum irrigation schedules (how much to apply and when). This research is briefly summarised below.

In arid/semi-arid regions, carrot yield and quality losses can be severe under restricted irrigation. For example, in Australia, Gibberd *et al.* (2003) demonstrated that reducing irrigation from replacing 151% of daily pan evaporation to 47% resulted in total and marketable yield losses of up to 91% and 97% respectively. Similarly, Imtiyaz *et al.* (2000) in Botswana demonstrated that irrigating with 18 mm at 55 mm cumulative pan evaporation (CPE) resulted in 90% marketable yield losses when compared to applying 18 mm at 22 mm CPE. In South Africa, Nortje and Henrico (1986) demonstrated that irrigating to field capacity at 80% depletion of soil moisture resulted in a 53% reduction in yield compared to irrigating at 20% depletion. In addition, root shape was poorer with less frequent irrigation regimes, but beta-carotene levels increased. In Arkansas, USA, Bradley *et al.* (1967) demonstrated up to a 50% increase in marketable yield over no irrigation with decreasing irrigation intervals (maximum yield was at 7 day intervals). However, Batra and Kalloo (1990a) found that carrots in India yielded only 6% more when irrigated at 80% of CPE compared to 40%. Irrigating at higher levels (120% of CPE) slightly reduced yields compared to 80% of CPE.

In more temperate climates, carrot response to irrigation is generally lower and more variable, due to the supplemental nature of irrigation to rainfall. For example, Orzolek and Carroll (1978) demonstrated in Delaware, USA, that irrigated carrots yielded 13% more than a non-irrigated crop. However, in Canada, Stiles (2002) demonstrated total and marketable yield reductions of 33% and 38% for a non-irrigated crop compared to irrigated. Similarly, in Norway, Riley (1989) demonstrated that irrigating to field capacity at a soil moisture deficit of 20 mm resulted in an average total and marketable root yield increase of 25% and 33% over irrigating at 40 mm and 60 mm deficits respectively. More frequent irrigation tended to result in a greater proportion of roots of saleable size, but also resulted in more split and fanged roots. The supplemental effect of carrot irrigation in a temperate climate was highlighted by Martin *et al.* (2004) in New Zealand. In this research, a mobile shelter was used to demonstrate a 75%

reduction in carrot yield in fully droughted plots compared to those that were fully irrigated.

In the UK, irrigation trials have provided even more variable results. For example, Bailey (1990) reported that trials in the 1960s showed little benefit from irrigating carrots. However, trials at the same location in the 1980s showed yield increases due to irrigation of up to 22.3 t ha^{-1}. More recently, Groves and Bailey (1994) showed that irrigation on a light soil gave an increase in marketable roots of up to 146% in one trial and up to 303% in a second trial. Clearly, the results were highly dependant on the weather during the growing season in each year of the experimental trial. This further highlights the role of irrigation in the UK vegetable industry as supplemental to rainfall. Nevertheless, irrigation of carrot crops in the UK is undoubtedly crucial in many years to achieve reliable high yields of quality produce.

Carrot yields and quality are susceptible to irrigation timing. Riley and Dragland (1988), Sorensen *et al.* (1997) and Stiles (2002) demonstrated that yield and quality were typically considerably reduced by drought during early and mid-season. However, in a small number of their trials, Riley and Dragland (1988) and Sorensen *et al.* (1997) found that not irrigating during early growth stages sometimes resulted in a small increase in root yield and quality. Riley and Dragland (1988) considered that this may have been due to a slight increase in soil temperature aiding crop growth. In the UK, Groves and Bailey (1994) found a similar marginal increase in yield after early season drought, at the expense of a considerable increase in common scab (*Streptomyces scabies*) infection. Nevertheless, most irrigation guidance for carrots identifies the periods of germination and establishment through to root enlargement as critical for ensuring adequate water supplies for the crop (e.g. Rubatzky *et al.*, 1999; Stiles, 2002; Fritz *et al.*, 2004; Will, *pers. comm.* 2005). However, it should be noted that most guidelines do not advocate irrigating carrots before the 4 true leaf stage due to the increased risks of physical damage and disease to the crop (Bailey, 1990; Groves and Bailey, 1994; Schoneveld, 1994; Sorensen *et al.*, 1997; Wright, *pers. comm.* 2005).

Carrots may also be affected by untimely or excess irrigation. Yields can be reduced in waterlogged conditions (Saiful Islam *et al.*, 1998) and root quality can also be affected. Irrigation, particularly from overhead systems, can also encourage some foliar and root diseases. Further details on the impacts of untimely or excess irrigation on carrot crops can be found in Section 6.4.

The effect of non-uniform irrigation on carrot yield and quality has not yet been fully investigated. Sanden *et al.* (2000) and Koech (2003) examined the effect of non-uniform solid-set and raingun irrigation on carrot yield in California and Australia respectively. Neither researcher found a significant correlation between irrigation uniformity and carrot yield, primarily as a result of practical limitations of the studies and the effects of adverse weather conditions on field observations. In addition, neither study examined the impact of the timing of non-uniform irrigation on crop production, nor did they fully examine the effects of application uniformity on crop quality. In the UK, a farm trial by Revaho (2005) indicated that carrot yield and quality may be slightly increased by sprinkler irrigation compared against raingun systems. This small (but not statistically significant) yield increase was assumed to be the result of higher application uniformity under the sprinkler system. However, although the trial provided useful information relating to in-field irrigation management, no comparative assessment of uniformity was conducted and no scientific replication was reported.

4. Raingun irrigation simulation: Model selection, calibration and validation

This chapter presents the selection, calibration and validation of the raingun irrigation model. The suitability and data requirements of potential raingun models are first reviewed and assessed, leading to the selection of a suitable model appropriate for the research framework. The selected model is then described in more detail. Finally, field data collected for model testing is summarised, followed by model calibration and validation.

4.1. Raingun irrigation simulation model selection

4.1.1. Model requirements

In order to evaluate the effect of a range of equipment and management strategies on raingun non-uniformity and the consequent impacts on crop yield and quality, a model capable of simulating the application of irrigation water under different raingun parameters was necessary. The requirements of the model are summarised below:

i) The ability to realistically simulate wetted pattern distortion under a range of wind conditions;

ii) The facility to simulate raingun movement down a field for a number of pulls using real wind data inputs to provide a spatial grid of irrigation application;

iii) The capability to simulate irrigation applications using a range of equipment and management strategies (e.g. lane spacing, trajectory angle, sector angle, time of irrigation etc.);

iv) The capability to process a number of simulations automatically without manual input of for each scenario, and;

v) Outputs which are in a format that enables data-bridging between irrigation and crop growth simulation components of the integrated modelling approach.

In general, such models comprise of two parts: a sub-model which can simulate wetted pattern distortion under different wind conditions for a variety of raingun settings (gun type, nozzle type, pressure, trajectory angle, sector angle); and a second sub-model which simulates gun movement down a field by overlapping and summing the application depths. This second sub-model can either create the appropriate wetted pattern directly according to ambient wind conditions, or select the appropriate wetted patterns from a database created by the first sub-model.

A number of models for raingun/sprinkler irrigation have been developed which fall into four main categories: statistically descriptive models, empirical models, semi-empirical models, and mechanistic models. These modelling approaches are briefly described below along with their data requirements and suitability for this research.

4.1.2. Statistically descriptive models

Statistically descriptive models include those developed by Elliot *et al.* (1980), Tsakeris *et al.* (1984), Mantovani *et al.* (1995) and Li (1998). These describe water application during an irrigation event or season from sprinklers or rainguns using various frequency distribution curves (e.g. normal, beta, gamma, Pearson distributions). Generally, these models require large amounts of catchcan data over a considerable period in order to generate appropriate frequency distribution curves. These approaches do not, however, simulate spatial distribution, or directly account for wind distortion. They are therefore not considered suitable for this research.

4.1.3. Empirical models

Empirical models for water distribution from sprinklers under differing wind conditions have been derived from experimental data. In similar work, Schull and Dylla (1976a,b), Oakes and Rochester (1981), Dalvand (1986) and Musa (1988) collected data from stationary sprinkler/raingun application patterns under a variety of wind conditions and linked them with distribution models to simulate field level irrigation. Detailed catchcan data for each raingun configuration were required for these models. Consequently, model outputs are restricted to rainguns with these characteristics. Furthermore, these methodologies did not take into account sector angles (all used 360° rotations) and tended to use only coarse (1 hour) or no wind variations during a pull simulation. These empirical models for raingun simulation are therefore somewhat limited in their application, and are not considered suitable for this research.

4.1.4. Semi-empirical models

Semi-empirical models offer a partial solution to the large amount of data required for empirical models by using a smaller data-set and extrapolating the results. Han *et al.* (1994) created a simple semi-empirical model for water distribution based on wind distortion of a wetted elliptical area. Calibration of the model required 170 different water application patterns. However, their model suffered from quite large variability errors.

Richards and Weatherhead (1993) generated equations to describe wetted pattern distortion due to wind based on the data generated by Dalvand (1986) and Musa (1988). They assumed that the wind effects on drifting and range shortening of a "zero-wind" application pattern was caused by disruption of the air flow that the water jet induces. The disruption of this air flow was assumed to be proportional to the wind velocity component which is at right angles to the water jet as it leaves the nozzle. The model could be calibrated for any equipment and operation setting using only three field-tested water application patterns – one under still conditions and two under different wind speeds. This approach also has the benefit of allowing sector angle effects to be considered. Al-Naeem (1993) modified and linked this model with a field distribution model to simulate raingun non-uniformity at a field level. His model created the appropriate wetted pattern for the wind conditions experienced at the raingun as it moved down the field (rather than using a database approach).

Newell *et al.* (2003, 2006) further developed the work of Richards and Weatherhead (1993) and Al-Naeem (1993) to form the basis of a Windows™ based raingun simulation package entitled TRAVGUN. TRAVGUN further reduces the data input requirement for calibration, needing only three catchcan transects (perpendicular to travel direction) – again with one under still conditions and two under different wind speeds. The model allows the simulation of wetted patterns from a calibrated raingun under a range of wind conditions and sector angles. It also allows simulation of irrigation pulls using these wetted patterns, but only using average wind conditions for a pull rather than real-time data. These characteristics make TRAVGUN (linked to a field simulation model) potentially suitable for this research.

4.1.5. Mechanistic models

Mechanistic models describe the spatial distribution of water from sprinklers or rainguns using physical equations for droplet trajectory and air drag. Early simple models such as that developed Fukui *et al.* (1980) did not agree well with observed application patterns under windy conditions as noted by Richards and Weatherhead (1993). By modifying the drag co-efficients in this type of model Vories and von Bernuth (1985), Vories *et al.* (1987), Seginer *et al.* (1991) and later Carrion *et al.* (2001) improved the shape of the simulated wetted pattern. However, these drag co-efficient modifications required considerable amounts of field data, and the derived models did not account for sector angle effects.

Grose (1999) used multi-phase fluid dynamics combined with ballistic theory to describe droplet break-up from a raingun jet and predict the resulting water application pattern under windy conditions. Calibration of the model required detailed data on droplet size distribution for each raingun configuration. The model allowed the creation of a database of wetted patterns under a variety of wind conditions for a specified sector angle of the calibrated gun(s). This database was linked with a field application model and used in the NIWASAVE (NItrate and WAter SAVing) integrated modelling approach (Cemagref, 1999) to simulate the non-uniformity of raingun irrigation and its consequences on crop yield. The Grose (1999) model was therefore also potentially suitable for this research.

4.1.6. Summary and model selection

Following the above critical evaluation of the potentially suitable raingun irrigation models, it was apparent that two models could have been appropriate for this research, namely the Grose (1999) model and TRAVGUN (linked to a field distribution model).

The Grose (1999) model uses novel algorithms to mechanistically describe droplet trajectories under windy conditions and has previously been used in similar research to investigate the impact of raingun non-uniformity on crop production. This model was originally selected for use in this research, primarily as a result of academic links to the model development and application in NIWASAVE (Cemagref, 1999). However, it was difficult to acquire the relevant droplet distribution data for gun calibration and the code for the wetted pattern simulation model was no longer readily available. Consequently, the opportunities for examining the effect of different equipment and management strategies were somewhat restricted using this approach, being limited to the raingun characteristics for which the model was originally developed.

On the other hand, TRAVGUN requires relatively simple and easily obtained calibration data to enable the creation of a database of wetted patterns for a range of wind conditions and sector angles. This would allow greater flexibility for simulation when combined with a field simulation sub-model similar to that used by Grose (1999).

Therefore, TRAVGUN was subsequently selected in favour of the Grose (1999) model. It will be used as a sub-model to create a database of wetted patterns (after calibration and validation for a single raingun). A second sub-model entitled "TRAVELLER" (de Vries, 2006) was created to simulate field application from the raingun using real wind data. The TRAVGUN and TRAVELLER models are described in more detail below.

4.2. Model description

4.2.1. The TRAVGUN model

TRAVGUN is a semi-empirical model developed by Newell *et al.* (2003, 2006) as part of the Queensland Department of Natural Resources and Mines' Rural Water Use Efficiency initiative. The model was designed to simulate raingun performance under a range of wind conditions to assist irrigators to reduce irrigation non-uniformity. TRAVGUN develops and applies research by Richards and Weatherhead (1993) and Al-Naeem (1993) on wind deformation of raingun wetted patterns. Data inputs for calibrating TRAVGUN have been considerably reduced from the earlier work, requiring only catchcan measurements for a moving gun from three transects, one of which must be under zero wind conditions.

A detailed description of TRAVGUN is presented in Newell *et al.* (2003). A short summary is given here.

TRAVGUN operates using a Windows™ graphical user interface to input calibration data and simulate wetted patterns from a raingun under still and windy conditions. The model also has a function to simulate irrigation application at the field level for two pulls using wind rose data (i.e. a single summarised wind condition for the entire irrigation event). Three catchcan transects are required for calibration of TRAVGUN: one under still conditions and two under differing wind conditions. These inputs are used in an internal calibration routine to optimise parameters for equations to describe wind distortion of a zero wind wetted pattern. Using these equations, TRAVGUN can then be used to simulate wetted patterns under a range of wind conditions. The calibration and operation of TRAVGUN is described in more detail below.

Firstly, the zero wind transect is converted to radial leg data (application depth in a single dimension from the raingun to the perimeter of the wetted pattern), including an adjustment for sector angle, if used. The radial leg data is then converted into a best-fit cubic spline function to calculate the application depth at any point from a stationary gun under zero wind. Functions for wind drift and range shortening (derived by Richards and Weatherhead (1993) from wetted pattern data collected by Dalvand (1986) and Musa (1988), and further developed by Al-Naeem (1993)) are then used to simulate the windy calibration transects under the observed wind conditions. A powerful gradient search routine is then used to identify the optimum values for six constants in the wind drift and range shortening functions by minimising root mean square error (RMSE) between observed and predicted transect application depths.

The optimised equations for wind drift and range shortening for the raingun under consideration are not used to distort the wetted pattern under windy conditions, but rather to distort the spatial arrangement of simulated catch cans. Spatial distortion of the catch can arrangement is limited to integer values, resulting in a 1 m grid spacing. Water application in these cans is calculated using partial derivatives of the wind drift and range shortening equations. Sector angle effects are simply modelled as a proportional increase in application rates with decreasing sector angles from 360°.

Once TRAVGUN is calibrated, wind affected wetted patterns at a 1 m grid spacing can then be generated by selecting the appropriate wind speed (maximum of 5.5 m s^{-1}), wind direction and travel direction. For each pattern, the raingun is assumed to lie directly over the central catchcan. The derived wetted patterns can be saved as an array of application rates (mm hr^{-1}) in a text file.

To date, there is no published validation of the TRAVGUN model, although its authors are in the process of publishing their research. However, the models from which TRAVGUN was developed have been previously validated against measured wind distorted wetted patterns. Both Richards and Weatherhead (1993) and Al-Naeem (1993) found that the simulated wetted patterns agreed well with observed data, typically explaining 80-90% of the observed variations in application rate and with root mean square errors (RMSE) of 1.5-3.5 mm h^{-1}. A modified version of the Richards and Weatherhead (1993) model has also been validated by Augier (1996) and Montero *et al.* (2001) for use in NIWASAVE model simulations (Bruckler *et al.*, 2000; Lafolie *et al.*, 2000; Ruelle *et al.*, 2003).

4.2.2. The TRAVELLER model

Although the TRAVGUN software allows simulation of raingun irrigation at the field level, it uses only a single set of wind parameters for the duration of an irrigation event. However, wind conditions may vary considerably during a single irrigation pull (typically 10-20 hours, depending on pull length and gun speed) and throughout an irrigation event (typically 2-5 days, depending on field size). Therefore a model to simulate field application under real wind conditions was required. Musa (1988), Al-Naeem (1993) and Grose (1999) separately developed such models. However, they either operated with a wind data interval which was too coarse, consumed excessive processing time or were not available for this research. Consequently, a new model termed "TRAVELLER" (de Vries, 2006) with a simple Windows™ user interface was developed (Appendix B). This model simulated the field level application of raingun irrigation using a database of wind affected wetted patterns generated by the TRAVGUN model. A brief summary of the TRAVELLER model is given below.

The irrigation simulation area in the TRAVELLER model is determined as a 5 m grid from x=0, y=0 (situated in the top left corner) to x=300, y=300 containing four raingun pulls which run down the y axis (Figure 4.1). This is defined as the reference field shape for all subsequent simulations. Each pull is simulated consecutively, with the raingun starting at y=0 and moving in discrete 5 m steps down the field until y=300. The length of time that the raingun spends at each discrete location during a pull is determined by the pull speed (specified by the user). The x co-ordinates (i.e. the lane spacing) in 5 m intervals and the start time for each pull are also specified by the user.

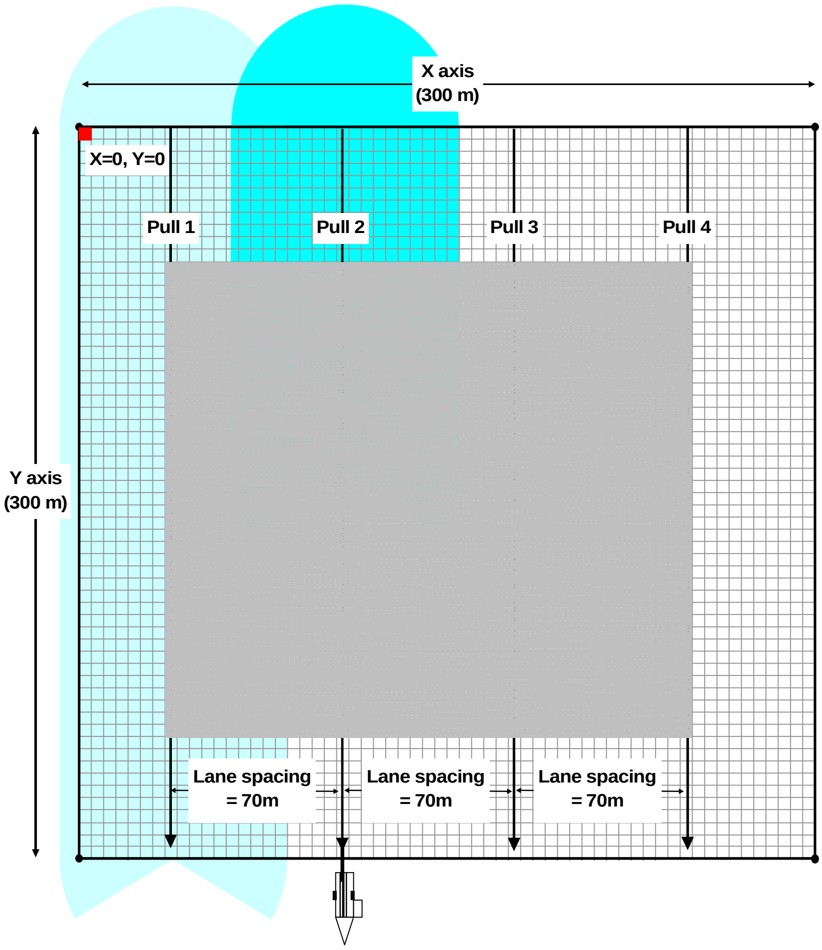


Figure 4.1 *Field layout in the TRAVELLER model, showing a 70 m lane spacing. The shaded grey box indicates area for uniformity calculation at this lane spacing.*

The TRAVELLER model uses a database of wetted patterns to simulate irrigation application within the defined area according to ambient wind conditions. The database is derived from wind affected wetted patterns generated by the TRAVGUN model for 0-10 m s^{-1} in 1 m s^{-1} intervals using 10° increments in wind direction. Each of the TRAVGUN wetted patterns is converted from a 1 m grid spacing by selecting the application points which correspond to a 5 m grid using a computer program (Appendix B). For the period which the raingun spends at each discrete position during a pull, the TRAVELLER model identifies the relevant wind speed and direction from 15 minute interval climate data and selects the appropriate wind affected wetted pattern for the ambient conditions. The depth of irrigation applied is then calculated from the elapsed time at that raingun location for the application rates described in the selected wetted pattern file. Irrigation applied at subsequent raingun positions for each pull is calculated in the same manner. The total application depth for each 5 m grid square during the simulated irrigation event is then summed and output as an array in a text file with a user-defined name. Note that for the calculation of application uniformity, only the relevant area between the travel lanes of the first and last pull (discounting the top and bottom 50 m of the field) are used in order to exclude edge effects (Figure 4.1).

The simulation parameters for each individual irrigation event are defined by the user in a text file. These values provide the simulation number and name for the output file title, the wetted pattern database to be used (allowing selection of any raingun characteristic, pressure, trajectory and sector angle database which has been created), the field orientation relative to prevailing wind, the wind data file to be used, and the pull speed, start times and lane spacing for each simulation.

The combined raingun simulation model, using the TRAVGUN model to generate wind affected wetted patterns and the TRAVELLER model to apply irrigation at the field level, can thus be used to simulate raingun irrigation under a range of equipment and management strategies. These include raingun make/model, nozzle type/size, water pressure, trajectory angle, sector angle, field orientation relative to prevailing wind, pull speed, pull start times and lane spacing. This combined model is hereafter referred to as the TRAVGUN-TRAVELLER model. The field data collected for testing the TRAVGUN-TRAVELLER model and the calibration and validation process are presented below.

4.3. UK field data for calibration and validation of the TRAVGUN-TRAVELLER model

Data for use in the calibration and validation of the TRAVGUN-TRAVELLER model were collected from two field sites in 2003 and 2004 located on commercial vegetable farms in East Anglia (termed site “I2003” and site “R2004”) (Figure 4.2). A detailed description of the sites, the field sampling methodology and a summary of the data collected are presented below. The additional sampling methodology for soil and crop growth data collection from each of the study sites is presented in Chapter 5.

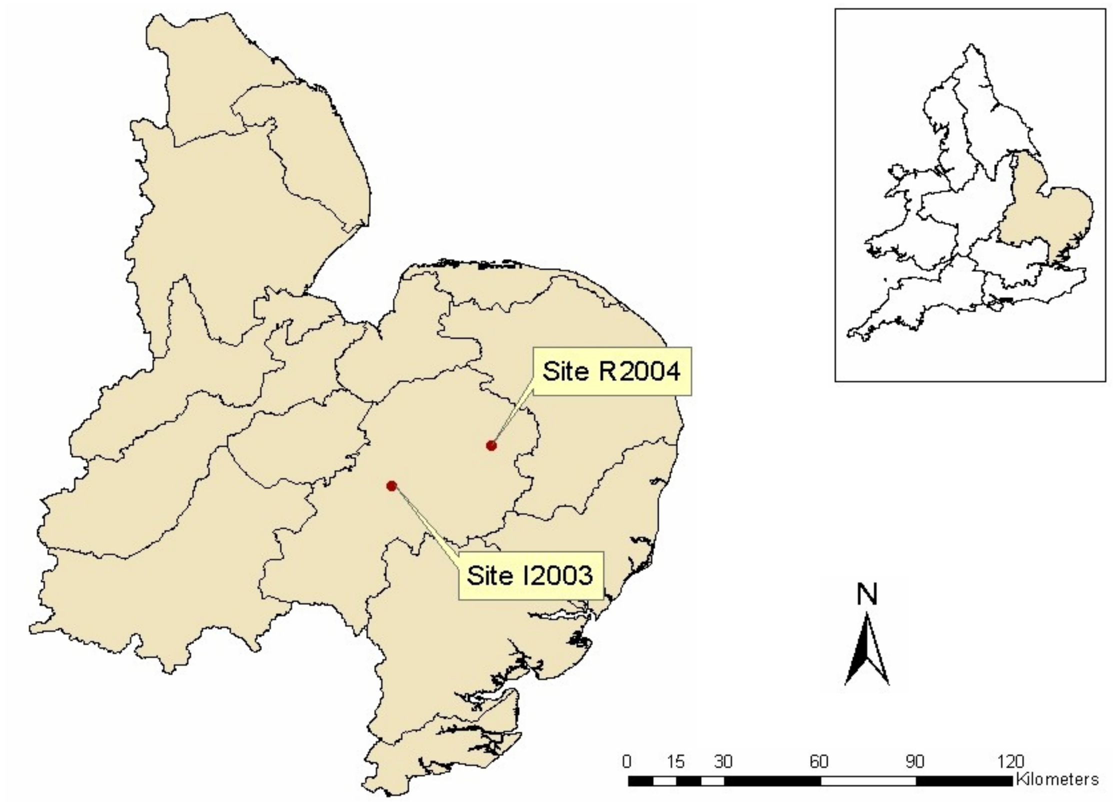


***Figure 4.2** Location of the two field sites (I2003 and R2004) used for irrigation, climate, soil and crop growth data collection in 2003 and 2004. Shaded area indicates the Environment Agency Anglian Region showing CAMS boundaries.*

4.3.1. Site I2003

This 10 ha site was provided by Tompsett Burgess Growers Limited and was located on the Cambridgeshire fens (52:21:20.064N, 0:22:12.019E, 0 m above sea level). The site was virtually level and flat, with a relatively uniform surface soil. On the eastern margin there was an approximately 15 m high shelter belt of poplars. To the south there was a hedge of approximately 2.5 m high and to the west a small area of scrub surrounding a pond and large machinery shed. The northern headland (where the hose-reel was located) was open.

Figure 4.3 illustrates the layout of the field site study area. Five raingun pulls were required to cover the area. Thirteen 5 m square plots spaced at 25 m intervals were carefully marked out on two transects across the field (at 100 m and 200 m from the hose-reel). The applied irrigation at each of these plots was measured using catchcans during the season. Further catchcans were placed between these plots on the 200 m transect to create a continuous transect line across the site. Three plots of one row wide by 2.4 m long were sheltered with mobile covers from all irrigation during the season. These non-irrigated plots and 10 randomly selected plots from the 26 catchcan plots were used to collect soil and crop data for crop growth modelling.

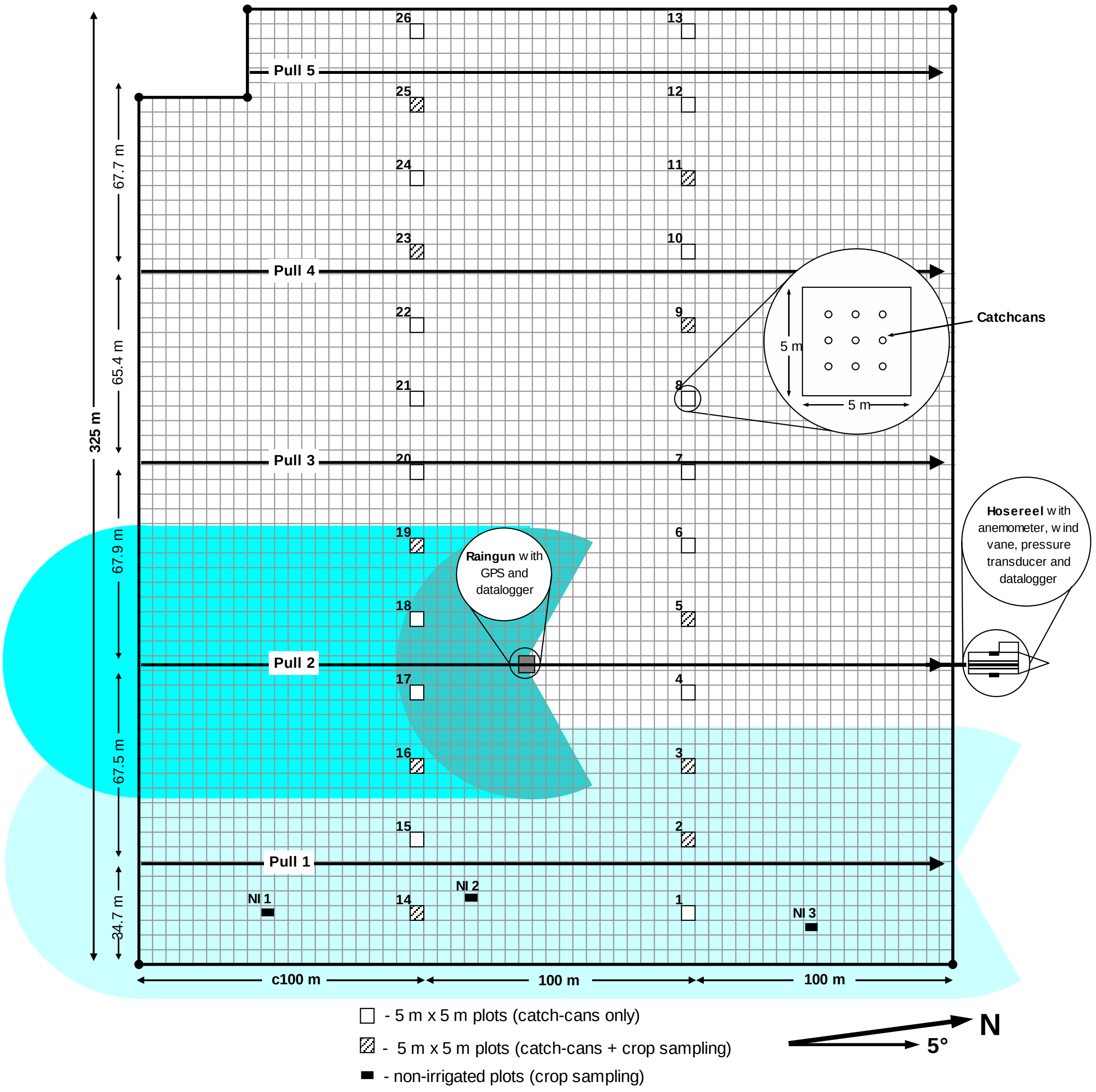


Figure 4.3 *Site I2003 field layout showing study plot locations and travel lane direction and spacing.*

The site was irrigated using a Wright Rain Super Touraine 110® fitted with a 400 m hose and a Nelson Big Gun SR150® raingun with a 24 mm ring nozzle. The raingun trajectory angle was 24°, and the sector angle was measured as 270° (although this was occasionally altered through the season). The irrigation water was supplied via an underground pressurised mains system connected to temporary pipes with hydrants located near the travel lanes. The lane spacing as measured during a typical irrigation event is shown in Figure 4.3, but varied by up to approximately 5 m between events. A global positioning system (GPS) and datalogger were mounted on the raingun to record its position in the field. Water pressure, wind speed and wind direction were also measured and continuously logged at the hose-reel. Climate data was obtained for 1998-2004 from an automated meteorological station approximately 0.7 km from the site (denoted I1998-I2004 for clarity).

4.3.2. Site R2004

This 12.7 ha field was provided by W.O. and P.O Jolly Ltd. and was located in the Brecklands of Norfolk (52:26:33.992N, 0:51:31.782E, 35m above sea level). The site had relatively uniform surface soil and was slightly undulating, with an overall slope of about 1° running down towards the hose-reel location. Just beyond the north-eastern corner, Scots pine trees rose to approximately 20 m high and beyond the southern edge, trees and scrub rose to approximately 10 m high. There were also a few individual trees along the eastern edge, but the western headland where the hose-reel was located was open.

Figure 4.4 illustrates the layout of the study area. The field required 6 ½ pulls for complete cover, with two pulls per day (day and night). The study area was restricted to the inner 4 pulls, and was irrigated using the same raingun throughout. Twelve 5 m square plots were carefully marked out every 20 m in each of two transects (again 100 m and 200 m from the hose-reel). The applied irrigation at each of these plots was measured using catchcans during the season. Further catchcans were placed between these plots on the 200 m transect to create a continuous transect line across the site.

Three of the 5 m by 5 m plots were sheltered using mobile covers for part of each application (denoted “semi-irrigated”, SI) and a further three were covered for all irrigations (“non-irrigated”, NI). Plots which received the full irrigation (subject to non-uniformity) were denoted “fully irrigated” (FI). All SI and NI plots and five randomly selected FI plots were used to collect soil and crop data for crop growth modelling. In order to reduce the effect of lateral water movement and to prevent water running through sheltered plots along the wheelings, a combination of earth bundings, ditches and heavy gauge polythene sheeting was used (Figure 4.5)

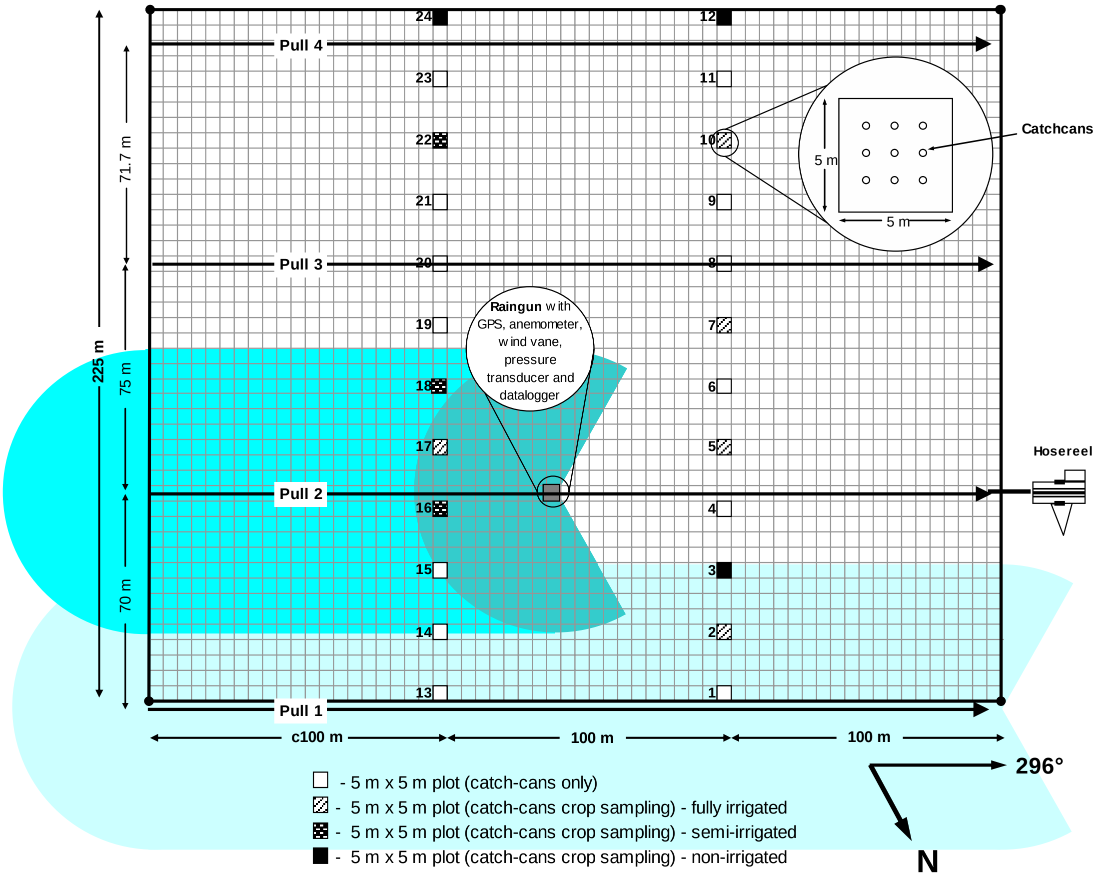


Figure 4.4 *Site R2004 field layout showing study plot locations and travel lane direction and spacing.*

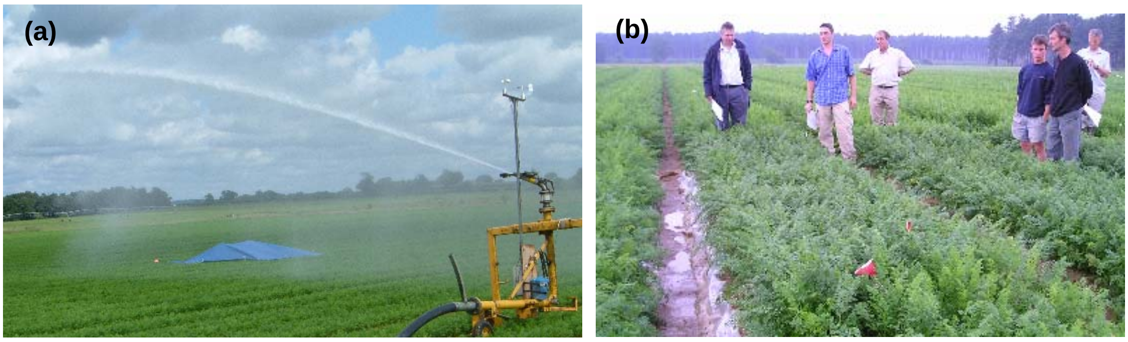


Figure 4.5 *Non-irrigated plot covered with tarpaulin at site R2004 (a). Bunding and polythene sheeting used to reduce lateral water movement in non-irrigated plots at site R2004 (b). Note droughted (darker) plants behind red marker.*

The site was irrigated using a Perrot SA® hose-reel fitted with a 300 m hose and a Nelson Big Gun SR150® raingun with a 25.4 mm taper nozzle. The raingun trajectory angle was 24°, and the sector angle was measured as 284°. The irrigation water was supplied through a pressurised mains system, with hydrants spaced along the western headland where the hose-reel was located. The lane spacing as measured during a typical irrigation event is shown in Figure 4.4, but varied by up to 2 m between irrigation events. As at site I2003, a GPS and datalogger were fitted to the raingun. Water pressure and wind conditions at the raingun were also logged. A set of separate tests were also conducted using the same hose-reel raingun system to collect wetted pattern and gun flow rate data. Climate data was obtained for 1999-2004 from an automated meteorological station approximately 2.5 km from the site (denoted R1999-R2004 for clarity).

4.3.3. Catchcan data

Measurements of applied irrigation during each irrigation event at both field sites were required for evaluation of the typical application uniformity of raingun irrigation, for use in the calibration and validation of the TRAVGUN-TRAVELLER model and for use in crop growth modelling.

At both field sites, nine replicate catchcans (187 mm high by 208 mm diameter) in a regular grid (1.67 m spacing) within each of the 5 m by 5 m plots were used to measure the applied irrigation. During a number of irrigation events, further catchcans were placed at 1.67 m spacing on the 200 m transect between existing cans to create a continuous transect line across the site. Three catchcans outside the irrigated area were used to adjust for errors due to rainfall and evaporation of collected water during each measurement period.

A dry summer at site I2003 resulted in 8 irrigation events with a total design application of 207 mm (a typical year might be 6 irrigation events – equivalent to approximately 150 mm (Pope, *pers. comm.* 2003)). The first of these irrigations was applied pre-drilling in April and the second from the 27th of June. Both these irrigations were not recorded. The first pull of recorded irrigation event 1 and pull 4 of irrigation event 6 were also not recorded.

Table 4.1 summarises the observed irrigation applications at the catchcan plots for site I2003. Note that a number of non-wind related issues affected raingun performance during the season: a faulty drive-spoon mechanism and supply pressure losses during irrigation events 3 and 4; a different hose-reel raingun was used for part of irrigation event 6; and travel speed and sector angle were adjusted during a number of irrigation events (depending on operator). These issues, combined with wind effects resulted in very variable application uniformity through the season. The application uniformity during irrigation events 1, 5 and 6 was generally high (CU >79% and DU >61%) whereas uniformity during irrigation events 2, 3 and 4 was low (CU of 66% and DU <51%). Despite this variability in uniformity, the mean application during each event only varied from -9% to +14% of the scheduled depth, with total application being only 2% more than planned. The relatively high total seasonal uniformity compared to individual events seen in Table 4.1 is a common phenomenon (e.g. Pair, 1968) and results from the spatially variable nature of non-uniformity during individual applications. This effect is often cited by growers as a reason why non-uniform application during a single irrigation event is not critical to crop production. However, this is likely to be a misconception since previous research suggests that water shortages (or excess) during certain growth stages can be important to crop production (e.g. Stiles, 2002; Riley and Dragland, 1988; Sorensen *et al.*, 1997; Groves and Bailey, 1994).

Table 4.1 *Summary of the scheduled and mean observed irrigation depths applied to catchcan plots and the resulting CU and DU for each recorded irrigation event at site I2003. Note that a pre-drilling irrigation application and the first post-emergence application were not recorded. In addition, the first pull of irrigation event 1 and the fourth pull of irrigation event 6 were also not recorded.*

Irrigation event ***Date of irrigation***	**1** ***11-14 July***	**2** ***21-25 July***	**3** ***09-13 Aug***	**4** ***27-31 Aug***	**5** ***04-08 Sept***	**6** ***17-20 Sept***	**Total**
Scheduled application (mm)	22.0	30.0	25.0	25.0	30.0	25.0	157.0
Mean observed application (mm)	20.7	27.4	25.7	28.5	32.5	24.9	159.7
CU* (%)	**82**	**66**	**66**	**66**	**84**	**79**	**90**
DU* (%)	**71**	**44**	**49**	**51**	**79**	**61**	**87**

* CU and DU calculated between travel lanes of pull 1 and pull 5 where possible

Three catchcan transects across site I2003 were recorded (during irrigation events 3, 4 and 5) and are presented in Figure 4.6. The overall transect uniformity during irrigation events 3 and 4 was low to moderate, with some areas receiving <10 mm of water and others receiving nearly 60 mm resulting in a CU of <77% and a DU of <67%. On the other hand, application uniformity during irrigation event 5 was relatively high, with a minimum application depth of 20 mm and a maximum of 53 mm resulting in a CU of 83% and a DU of 76%. This was primarily due to the effect of the aforementioned faulty drive-spoon mechanism and supply pressure losses on application uniformity during pull 4 of irrigation event 3 and pulls 3 and 5 of irrigation event 4. The application uniformities of individual pulls (calculated assuming a simulated repeat pull at 70 m lane spacing) illustrated the impact of these equipment issues on application uniformity. For the affected pulls, the uniformity was very low (CUs of 34-65% and DUs of 2-43%) whereas uniformity was much better for non-affected pulls (CUs of 76-86% and DUs of 55-81%).

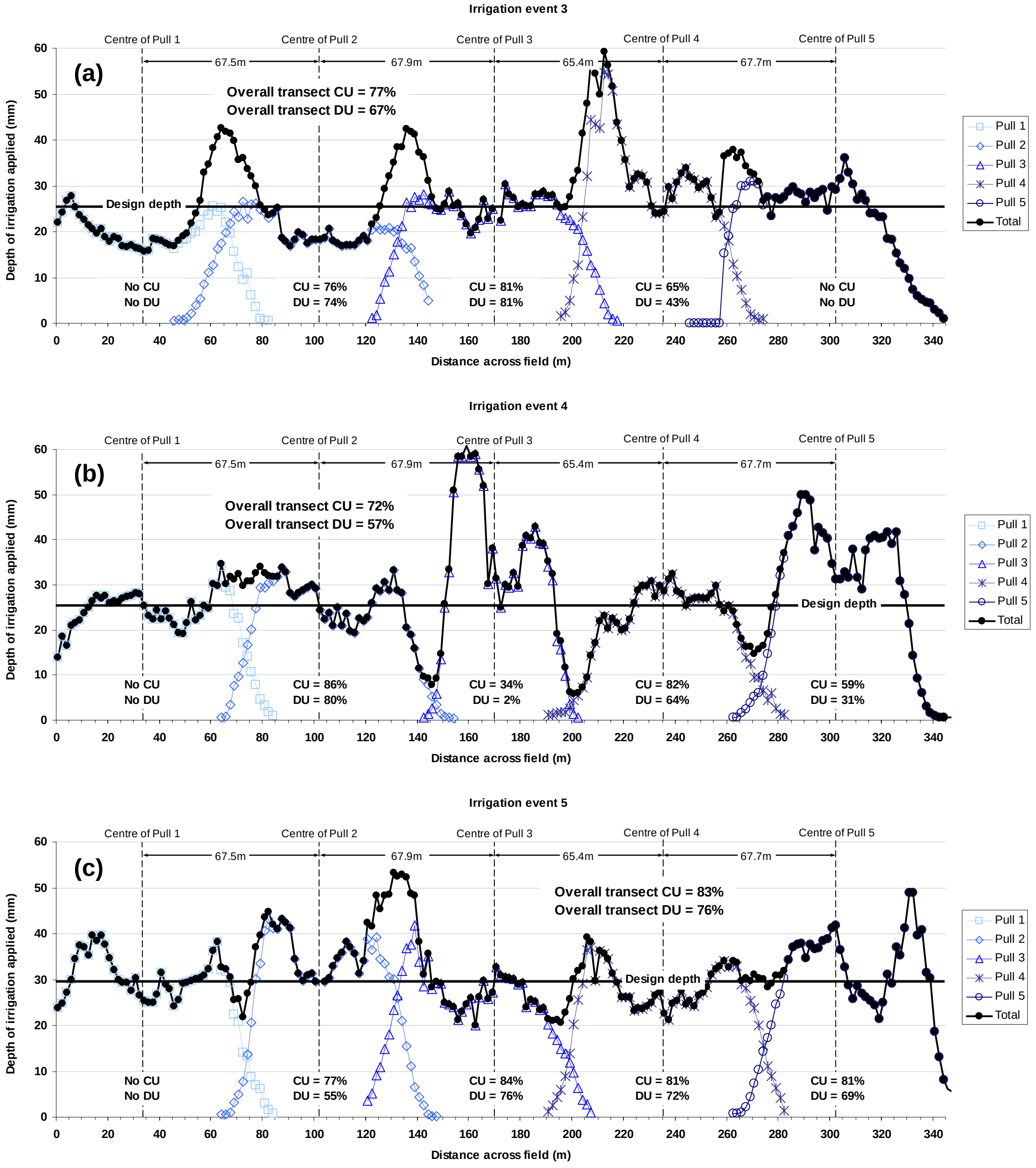


Figure 4.6 *Irrigation application at site I2003 across transects during irrigation event 3 (a), irrigation event 4 (b) and irrigation event 5 (c). CU and DU values for each pull were calculated assuming a simulated repeat pull at 70 m spacing. No CU or DU could be calculated for Pull 1 due to edge effects.*

At site R2004, a relatively dry start to the season resulted in six irrigation events with a total planned application of 150 mm by the beginning of August. However, sufficient rainfall occurred during August and September to require no further irrigations before harvest. All irrigation events were recorded. It should be noted that a problem with the hose-reel gearbox during pull 1 of irrigation event 5 resulted in a different reel being used to pull the same gun for the remaining pulls of that event.

Table 4.2 summarises the observed irrigation applications at the catchcan plots for site R2004 showing the design application depth, mean application, the CU and the DU for each irrigation event. The application uniformity during individual irrigation events was generally higher and less variable than at site I2003 (CUs of 70-85% and DUs of 50-75%). This was partly as a result of fewer mechanical difficulties, but possibly also as a result of differing wind conditions. It is interesting to note that, despite the generally higher application uniformity of individual irrigation events at site R2004 than site I2003, the total seasonal uniformity was slightly lower. The applied irrigation was on average 9% less than the scheduled application, resulting in 14 mm less irrigation applied over the season than intended. This was likely to have had implications for irrigation scheduling at the site, and may have had consequences for crop productivity.

Table 4.2 *Summary of the scheduled and mean observed irrigation depths applied to catchcan plots for each irrigation event at site R2004.*

Irrigation event *Date of irrigation*	**1** *03-05 June*	**2** *11-13 June*	**3** *16-18 June*	**4** *05-07 July*	**5** *25-27 July*	**6** *01-03 Aug*	**Total**
Scheduled application (mm)	25.0	25.0	25.0	25.0	25.0	25.0	150.0
Mean observed application (mm)	24.2	23.6	23.8	19.7	23.9	22.9	136.9
CU* (%)	**74**	**77**	**70**	**83**	**80**	**85**	**89**
DU* (%)	**57**	**69**	**50**	**72**	**75**	**75**	**83**

* CU and DU calculated between travel lanes of pull 1 and pull 4 for fully irrigated plots only

Five catchcan transects across site R2004 were recorded (during all irrigation events except the first). Figure 4.7 illustrates the variability in application uniformity across the site during irrigation events 2, 3, and 6. The overall application uniformity during irrigation events 2 and 3 was relatively low, with a number of areas receiving almost no irrigation and others receiving more than 40 mm, resulting in a CU of <72% and a DU of <55%. On the other hand, application uniformity during irrigation event 6 was relatively high overall with a CU of 82% and a DU of 73% (despite also having a number of areas with almost no irrigation and some with nearly 40 mm). The application uniformity of individual pulls varied widely, from a CU of 31% to 89% and a DU of 2% to 86%. Since there were no significant equipment issues during these irrigation events, the variations observed in application uniformity can be concluded to be primarily a result of the ambient wind conditions.

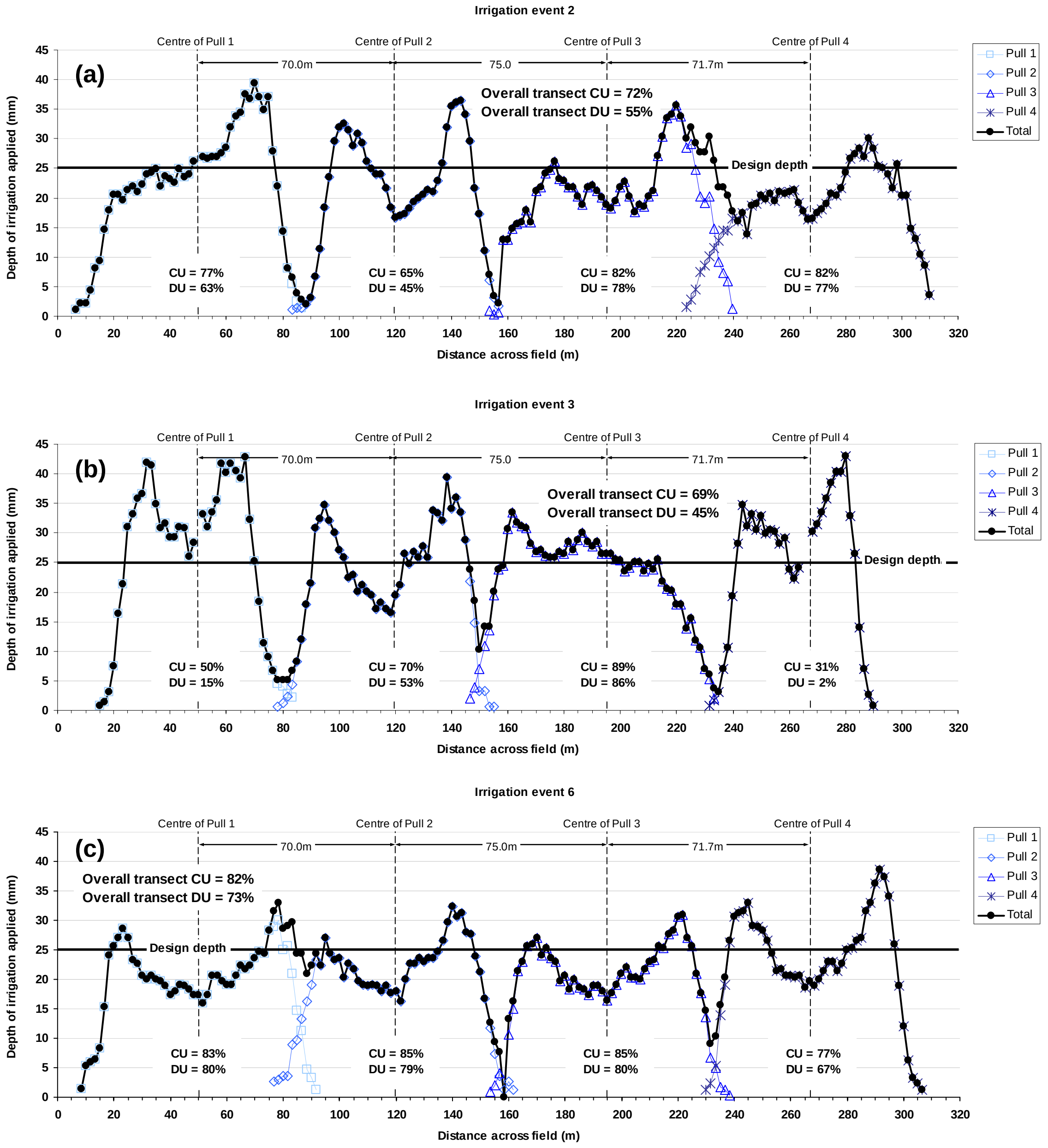


Figure 4.7 *Irrigation application at site R2004 across transects during irrigation event 2 (a), irrigation event 4 (b) and irrigation event 6 (c). CU and DU values for each pull were calculated assuming a simulated repeat pull at 70 m spacing.*

4.3.4. GPS data

GPS data recording the raingun position and pull speed were required in order to determine the pull start and finish times and to verify the raingun pull speed for use in the calibration and validation of the TRAVGUN-TRAVELLER model.

At both field sites, a Trimble Pathfinder Pocket® GPS was fitted to the raingun carriage in a waterproof casing (Figure 4.8). The location of the gun was recorded at 1m intervals and logged on a Compaq iPAQ H3850 Pocket PC® using Trimble TerraSync® software. Both devices were powered by a 12 volt, 7 amp-hour or 12 amp-hour battery, which was re-charged between pulls.

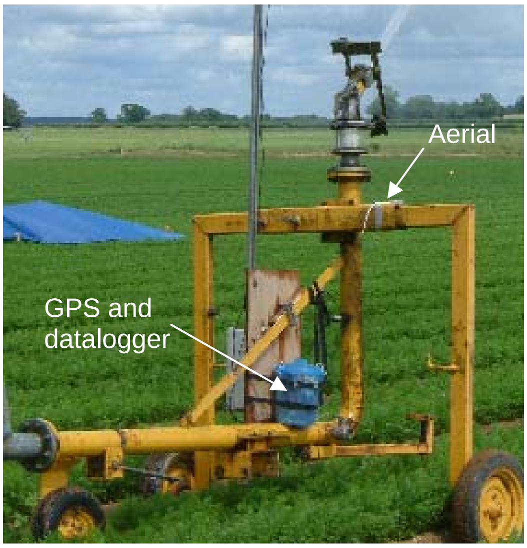


***Figure 4.8** GPS equipment mounted on raingun at site R2004.*

The recorded GPS data was then differentially corrected using data from King's Lynn base station (46 km distant), obtained from the National GPS Network website operated by the Ordnance Survey.

However, the data was found to be of poor quality (Figure 4.9), with the results indicating a lateral raingun movement of up to 40 m. This was thought to be a result of the raingun barrel and/or spray causing signal interference as it passed over the aerial. Consequently, the GPS data could not be used either to determine pull start/finish times or to check the accuracy of raingun pull speed. The start/finish times for raingun pulls were therefore determined from water pressure measurements (although this was not possible at site I2003 due to equipment malfunction and the location of the metering point on the hose-reel) and the raingun pull speeds displayed on the user interface of the hose-reel were assumed to be accurate.

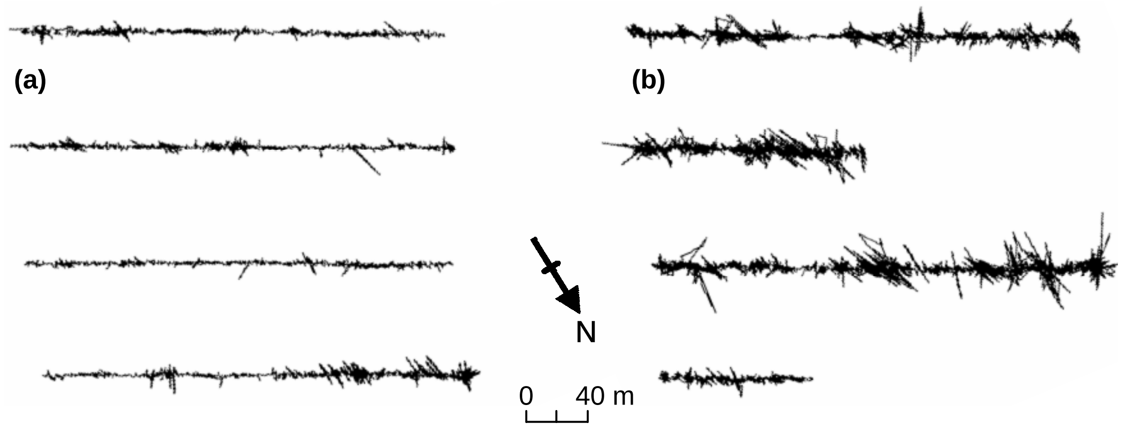


Figure 4.9 *Illustration of the poor quality GPS data recorded at both field sites showing raingun movement during irrigation event 3 (a) and 6 (b) at site R2004. Note that pulls 1 and 3 of irrigation event 6 were also incomplete datasets.*

4.3.5. Water pressure data

Water pressure measurements were required in order to determine raingun pull start/finish times and to verify water pressure at the raingun for use in the calibration and validation of the TRAVGUN-TRAVELLER model.

At site I2003, a 0-10 bar TransInstruments Series 2000® pressure transducer (RS 249-3858) was fitted to the raingun supply pipe located after the turbine on the hose-reel. Water pressure was measured every second and averaged over a 30 second period before logging to a Campbell CR10X® data logger (also used for logging wind data). At site R2004, however, the equipment was fitted to the riser of the raingun (just visible in Figure 4.8, above the GPS box).

The monitoring equipment malfunctioned at site I2003, resulting in no useable data. Manual measurements carried out using a separate pressure gauge fitted to the raingun riser indicated that the system was generally operating at 5.5-6.0 bar. However, during irrigation event 6, when two rainguns were operating in the field, the pressure measured at the riser fell to 3.2 bar.

The pressure recording equipment also malfunctioned at site R2004, resulting in no data for irrigation events 2 and 3. However, data was collected for all other irrigation events. Figure 4.10 illustrates the measured variation in water pressure at the raingun riser during irrigation event 4. The mean water pressure during the four recorded irrigation events was 4.2 bar. Water pressure generally varied little between and during irrigation events. A small difference of 0.1-0.3 bar was observed between different pulls (most likely a result of wear on the hydrants). During individual pulls, a gradual increase of about 0.1-0.2 bar was observed as the gun neared the hose-reel, often in fluctuating steps of 0.1-0.2 bar. Sudden pressure increases or decreases of up to 0.5 bar were observed when other irrigation equipment on the same water distribution spur was switched on or off. Occasionally, other fluctuations of up to +/- 1 bar were observed, thought to be due to the operation of other irrigation equipment on the farm. The different hose-reel used during irrigation event 5 showed smaller and less fluctuating pressure changes than the study reel, indicating that pressure variations during irrigation may be associated with mechanical operation of the system.

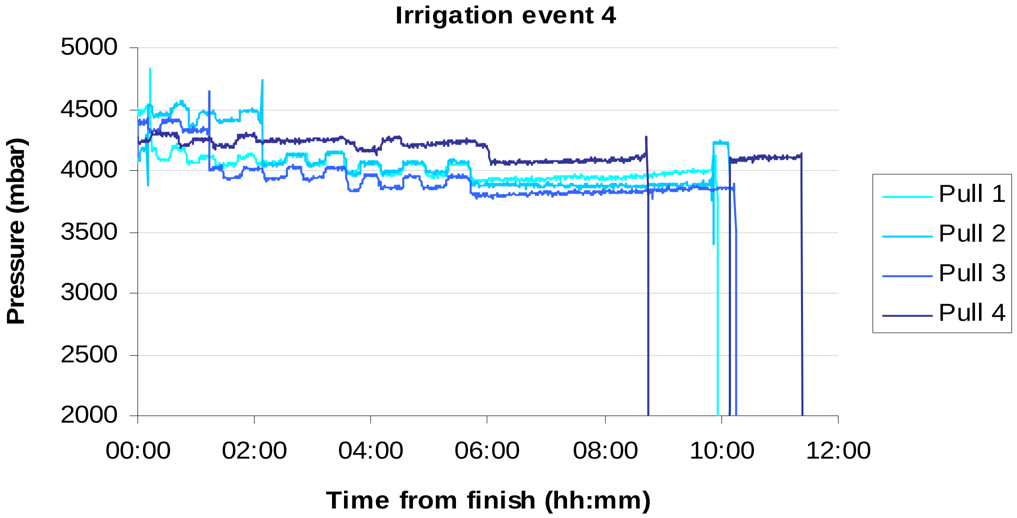


Figure 4.10 *Measured water pressure at the raingun riser during irrigation event 4 at site R 2004. Note that pull 4 suffered from system pressure loss near the start of the pull.*

4.3.6. Wind speed and wind direction data

Wind speed and wind direction data recorded during irrigation events were required in order to assist in evaluating the typical application uniformity of raingun irrigation and for use in the calibration and validation of the TRAVGUN-TRAVELLER model.

At site I2003, a Vector Instruments A100R® anemometer and W200P® wind vane were mounted on a mast fixed to the hose-reel. The mast extended to c5 m from the ground (c1.5 m above the reel) to reduce the effect of the structure on wind flow. At site R2004, the equipment was mounted on the raingun carriage, with the mast rising to c3.2 m from the ground to reduce the effect of the water jet on air flow (Figure 4.11). Data was logged to a Campbell CR10X® datalogger (also used for logging pressure data) as the wind speed over a 30 second period (m s^{-1}) and the wind direction every 30 seconds. Wind directions were corrected for mast orientation and rounded to the nearest 10 degrees. The mode of this value was used to determine the prevailing wind direction during irrigation events.

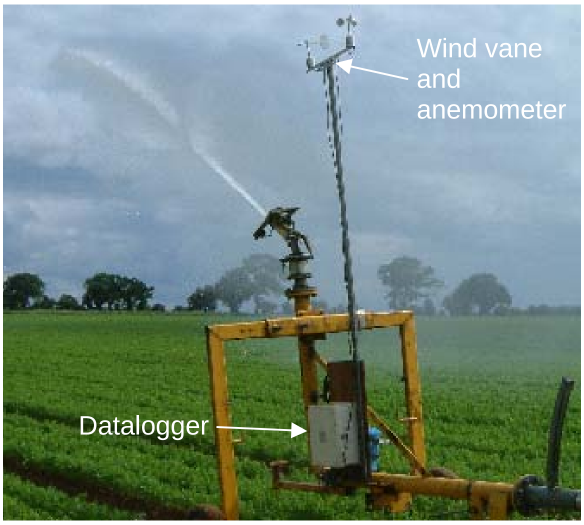


Figure 4.11 *Anemometer, wind vane and datalogger mounted on the raingun carriage at site R2004.*

Owing to the failure of the pressure recording equipment and the variability in pull speeds used at site I2003, it was difficult to ascertain the pull start/finish times necessary to determine the wind conditions during irrigation (particularly for the period when the raingun was passing the catchcan transects).

Using estimated pull times, it was calculated that the mean wind speed during each irrigation pull at site I2003 was typically about 3.2 m s^{-1} but varied between 1.1 m s^{-1} and 6.8 m s^{-1} with gusts of up to 11.0 m s^{-1}. Wind speeds were highly variable, with coefficients of variation during each pull typically being about 45% but varying between 21% and 90%. Wind direction during each pull and between pulls was also quite variable. The prevailing wind for the majority of pulls was from the north or north-east, although a relatively large proportion of pulls were subject to winds from the south-west. Since the direction of raingun travel at site I2003 was 5°, this meant that the majority of winds during irrigations had a strong component parallel to the raingun travel axis.

At site R2004, pressure data was available for most pulls in order to determine start/finish times and consequently the period when the raingun was passing the catchcan transects. For irrigation events where no pressure data was available, manually recorded start times and raingun pull speed were used to determine this period. The mean wind speed and mode wind direction during each entire pull and for the period when the raingun was passing the catchcan transect were calculated.

The mean wind speed during each pull was typically lower at site R2004 than at site I2003, being about 2.6 m s^{-1} and ranging from 0.8 m s^{-1} to 5.7 m s^{-1} with gusts of up to 11.4 m s^{-1}. Wind speeds were slightly less variable than at site I2003 with a typical coefficient of variation of about 40%, ranging between 22% and 71%. Wind directions were also slightly less variable, with prevailing winds generally from the west and south-west, although a relatively large proportion were from the east. Since the direction of raingun travel at site R2004 was 296°, this meant that the majority of winds had a strong component parallel to the raingun travel axis.

Figure 4.12 illustrates the effect that wind speed and direction had on the irrigation uniformity of each pull in the five full transects carried out at site 2004. It can be seen that high mean wind speeds of above about 3 m s^{-1} and winds which had a strong component parallel to the travel axis tended to result in the lowest uniformity. Conversely, low wind speeds and winds which were perpendicular to the travel direction tended to result in higher uniformity. This behaviour is typical for raingun irrigation.

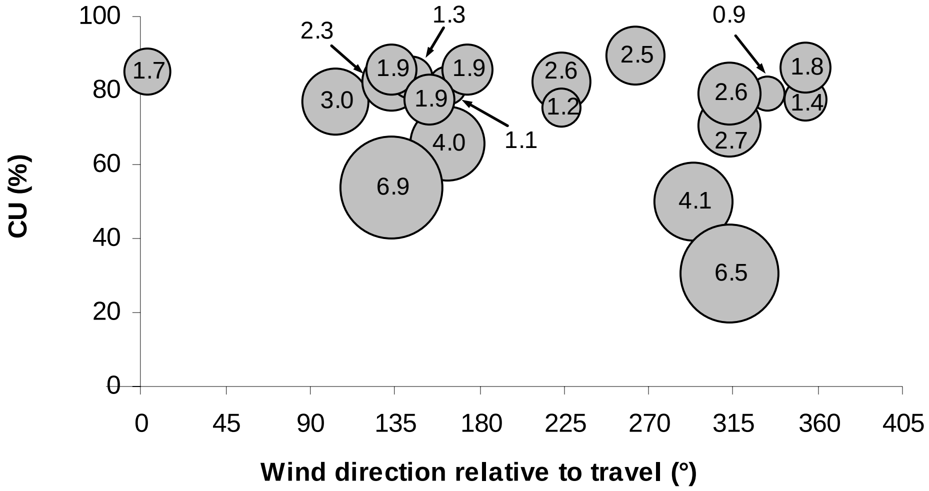


Figure 4.12 *Effect of wind speed and direction on CU of all individual pulls at site R2004. Size of circles represents the mean wind speed recorded during irrigation of transects (denoted inside circles in m s^{-1}).*

4.3.7. Wetted patterns and raingun flow rate data

Wetted patterns and raingun flow rate data were required to assist in the calibration and validation of the TRAVGUN-TRAVELLER model.

Seven wetted patterns for the hose-reel raingun used at site R2004 were collected following the international standard ISO 7749-2:1990 (ISO, 1990). Catchcans were laid out in a 5 m grid with the raingun in the centre, equidistant between four cans. The raingun was operated with the clutch disengaged and the sector stops removed to allow 360° rotation for approximately one hour. Rotation both anti-clockwise and clockwise was induced at a ratio of 1:2.89 (derived from measurements with sector stops in place). The raingun start and finish positions during measurements were in the same location, with the raingun aimed between cans. The water pressure, wind speed and wind direction at the raingun were recorded using the same method as described previously.

Figure 4.13 illustrates wetted pattern measurement under relatively strong wind conditions, showing the catchcan grid layout. The effect of wind in distorting the trajectory of water from the main jet can clearly be seen. Three of the observed wetted patterns are illustrated later in Figure 4.14.

Mean wind speeds recorded during each wetted pattern measurement ranged from low (0.7 m s^{-1}) to relatively high (3.7 m s^{-1}), with maximum gusts of up to 6.1 m s^{-1}. The prevailing wind direction during each wetted pattern measurement was predominantly from the west but occasionally from the south or the north (see Table 4.4).

Figure 4.13 *Wetted pattern measurement at site R2004 under a wind speed of approximately 3.7 m s*$^{-1}$.

4.4. Calibration and validation of the TRAVGUN-TRAVELLER model

Calibration and validation of the TRAVGUN-TRAVELLER model was carried out in two stages – calibration and testing of the TRAVGUN model component and validation of the TRAVGUN-TRAVELLER field level simulation model.

The TRAVGUN model requires a calibration dataset collected for the raingun which is to be simulated. Data from site R2004 was used to calibrate and test TRAVGUN. No data from site I2003 was used due to the large degree of uncertainty introduced as a result of raingun and monitoring equipment malfunctions and the use of other rainguns on the site.

A number of calibrations were performed for TRAVGUN and were tested against wetted pattern data collected at site R2004 using the same hose-reel raingun system. The best-fitting calibration was then used to generate a database of wind affected wetted patterns for the raingun. This database was then used in validating the TRAVGUN-TRAVELLER model against catchcan transects collected at site R2004. The calibration and testing of the TRAVGUN model and the validation of the TRAVGUN-TRAVELLER model are presented below.

4.4.1. Calibration and testing of the TRAVGUN model component

Twelve calibrations for TRAVGUN were formulated, consisting of all combinations of two low wind transects (representing zero wind) and four windy condition transects (Table 4.3).

Table 4.3 *Wind conditions during transects used for TRAVGUN calibration.*

Wind conditions	Transect	Wind conditions during transect irrigation	
		Mean wind speed ($m\ s^{-1}$)	Prevailing wind direction relative to travel axis (°)
Zero wind	Irrigation 4 pull 1	0.9	334
	Irrigation 4 pull 3	1.1	164
Windy	Irrigation 2 pull 1	3.0	104
	Irrigation 2 pull 2	4.0	164
	Irrigation 3 pull 3	2.5	264
	Irrigation 4 pull 4	6.9*	134

*TRAVGUN accepts maximum wind speeds of 5.5 m s^{-1}, so this maximum value was used for calibration

The calibration routine of TRAVGUN optimises wind drift and range shortening equations for each of the calibration datasets. The optimised equations for each dataset were then used in the model to generate wetted patterns for comparison to observed wetted pattern data. Simulated wetted pattern application rates were compared to observed data using linear regression analysis in GenStat® v8.1. The proportion of variation in the data accounted for by the model (R^2) and root mean square error (RMSE) were calculated and used to determine the best fitting calibration dataset.

There was a large effect on model performance as a result of the combination of transects used for calibration (R^2 ranged from 20% to 87%). However, RMSE values did not vary much between the different calibration datasets – typically ranging from 2.5 mm h^{-1} to 4.5 mm h^{-1}. Therefore, the best fitting calibration dataset was selected based on R^2 and the closeness of the linear regression equation to unity.

The best fitting calibration dataset was that obtained by using Irrigation 4 pull 3 for zero wind and Irrigation 2 pull 2 and Irrigation 4 pull 4 for windy conditions. Table 4.4 and Figure 4.14 summarise the fit of wetted patterns generated using this calibration to the observed patterns. Compared to the observed data, the model tended to simulate relatively high application depths near the maximum throw range at low wind speeds (wetted patterns 1 and 5). Consequently, TRAVGUN explained between 59% and 65%

of the observed variation in application rates at these wind speeds. At moderate or higher wind speeds, model performance was good, explaining between 79% and 85% of the observed variation in application rates. However, it can be observed in Figure 4.14 that TRAVGUN tended to underestimate range shortening perpendicular to the wind direction and pattern elongation down wind. Considered over all seven wetted patterns, the model explained 76% of the variation in observed application rates with a RMSE of 3.33 mm hr^{-1}. It was therefore concluded that TRAVGUN provided a reasonable simulation of raingun wetted pattern application under a range of wind conditions.

Table 4.4 *Derived fit of wetted patterns generated by TRAVGUN to observed wetted patterns.*

Wetted pattern	**Mean wind speed (m s^{-1})**	**Prevailing wind direction relative to travel axis (°)**	**Model fit parameters**			
			R^2	**RMSE (mm h^{-1})**	**Intercept** ± standard error	**Slope** ± standard error
1	1.1	274	65.4	3.70	-0.447 ± 0.296	1.2498 ± 0.0454
2	2.2	14	82.9	2.77	0.489 ± 0.185	1.0409 ± 0.0236
3	2.3	14	84.7	2.64	0.259 ± 0.178	1.1414 ± 0.0243
4	3.7	64	79.0	3.38	1.323 ± 0.206	0.9778 ± 0.0252
5	0.7	264	59.3	3.92	-0.421 ± 0.327	1.2252 ± 0.0508
6	3.5	324	80.2	3.26	1.082 ± 0.202	0.9612 ± 0.0239
7	3.6	324	81.6	3.14	0.949 ± 0.196	0.9893 ± 0.0235
All	**-**	**-**	**76.4**	**3.33**	**0.6806 ± 0.0834**	**1.0417 ± 0.0109**

4.4.2. Validation of the TRAVGUN-TRAVELLER model

The TRAVGUN-TRAVELLER model was tested against catchcan transect data collected from site R2004. The model was parameterised using the raingun equipment and management characteristics for the site. Wind conditions recorded at the raingun were converted into 15 minute interval data (using mean wind speeds and the mode of wind directions rounded to the nearest 10°). Wind affected wetted patterns for the raingun were generated using the TRAVGUN model component for wind speeds from 0-10 m s^{-1} at intervals of 1 m s^{-1} and for all wind directions at 10° intervals. Since the maximum wind speed permitted in TRAVGUN is limited to 5.5 m s^{-1}, wetted patterns generated at this wind speed were assumed to represent those for wind conditions of 6 m s^{-1} and above. This database of wind affected wetted patterns was used in the TRAVELLER model component to simulate irrigation application for each of the five irrigation events during which catchcan transects were recorded.

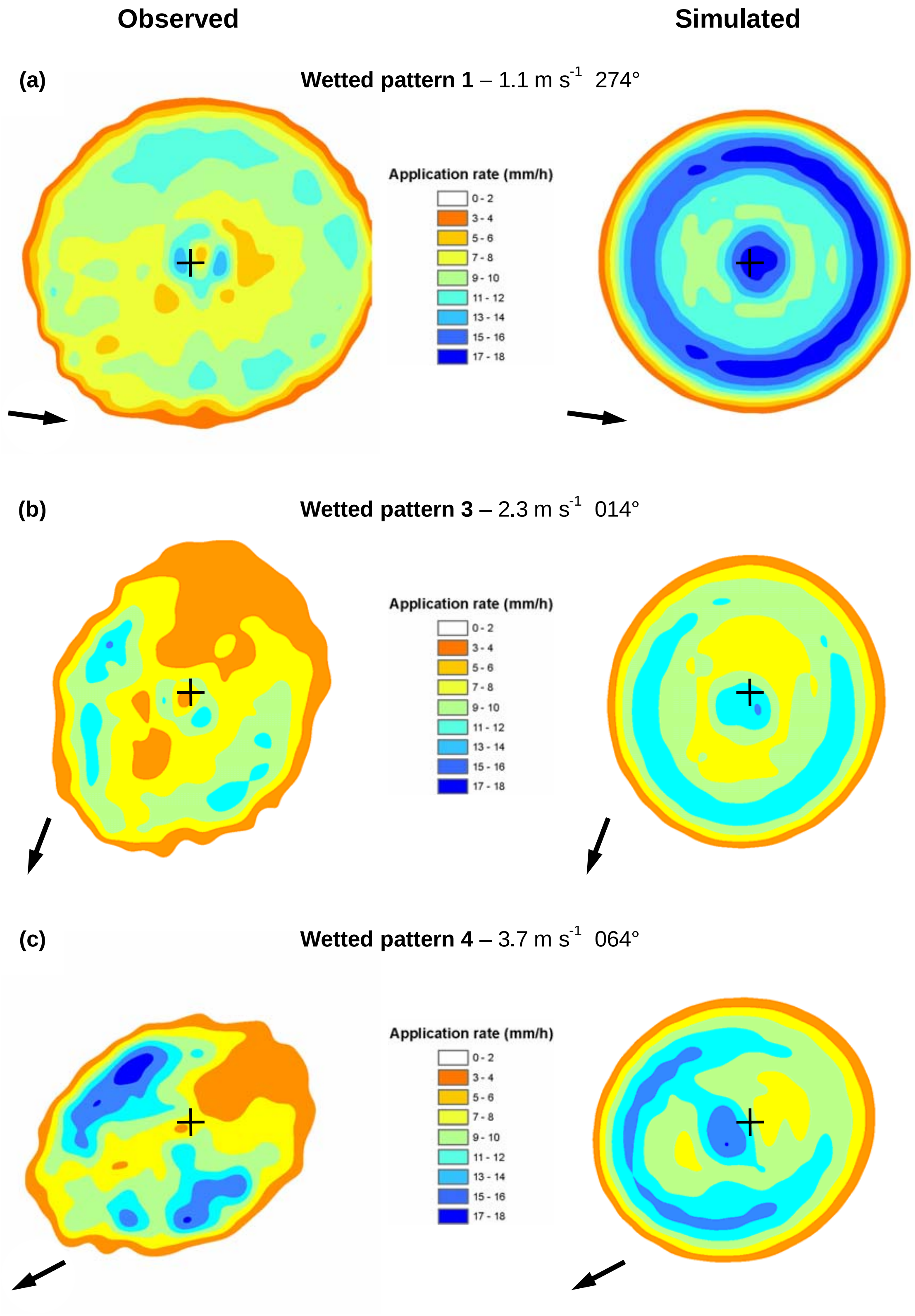


Figure 4.14 *Observed wetted patterns 1 (a), 3 (b) and 4 (c) from site R2004 versus patterns simulated using TRAVGUN showing wind speed and wind direction relative to travel.*

The relevant transects from the simulated data were then plotted against the observed catchcan transect data. Linear regression analysis was performed on the data and R^2 and RMSE values were generated (Table 4.5). Figure 4.15 illustrates the simulated and observed irrigation application depths for three transects (during Irrigation events 2, 4 and 6). Generally, the model performed acceptably, explaining between 29% and 70% of the observed variation in application depths in individual transects and 44% overall. Root mean square errors (RMSE) were reasonably high (between 4.9 mm and 7.9 mm).

The model fit would have been better were it not for a slight over-estimation of application depths in most transects (typically by about 2-6 mm), caused by simulating excessively high application rates near the maximum throw range, particularly under low wind speeds (e.g. pull 1 of irrigation events 4 and 6). In addition, simulated transects appeared to exhibit a slightly smaller degree of distortion due to wind conditions than was observed. Both of these issues relate to the wetted patterns generated by the TRAVGUN model component, which tended to have an exaggerated "doughnut" shape under low winds and relatively limited range shortening or pattern elongation under higher winds.

However, as a representation of typical raingun response to wind conditions during irrigation, it was concluded that the TRAVGUN-TRAVELLER model performed well enough to justify its use in evaluating the effects of changing equipment and management strategies on raingun non-uniformity.

Table 4.5 *Derived fit of transects generated by the TRAVGUN-TRAVELLER model to observed catchcan transect data.*

Transect in irrigation event:	**Model fit parameters**			
	R^2	**RMSE (mm)**	**Intercept ± standard error**	**Slope ± standard error**
2	31.2	7.39	11.72 ± 2.73	0.6310 ± 0.119
3	50.6	7.85	12.22 ± 2.19	0.9855 ± 0.868
4	38.3	6.65	12.87 ± 2.32	0.6410 ± 0.104
5	28.7	7.33	9.95 ± 3.42	0.7700 ± 0.153
6	70.4	4.88	3.73 ± 2.00	1.0708 ± 0.0894
All	**43.8**	**6.94**	**10.72 ± 1.09**	**0.7301 ± 0.0473**

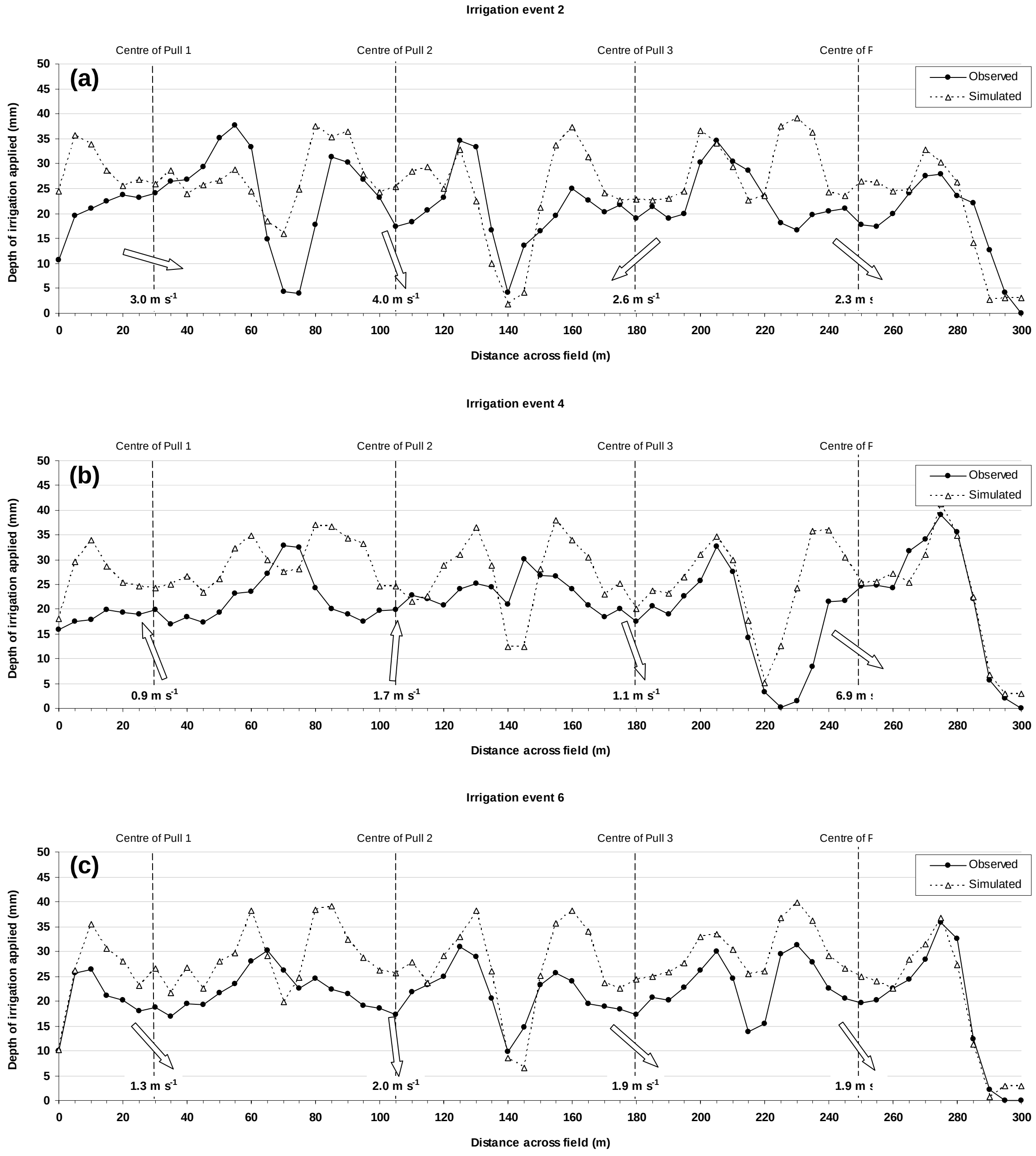


Figure 4.15 *Observed and simulated application depths along transects recorded during irrigation event 2 (a) irrigation event 4 (b) and irrigation event 6 (b) at site R2004. Arrows indicate wind direction relative to travel direction.*

4.5. Summary

A review of the raingun irrigation simulation models potentially suitable for use in this research originally identified a mechanistic model by Grose (1999). However, there were considerable limitations to using the Grose (1999) model resulting from the restricted options currently available for simulation and difficulties in re-calibrating the model to expand the simulation possibilities. Therefore, it was subsequently rejected in favour of a more flexible semi-empirical model entitled “TRAVGUN” (Newell *et al.,* 2003; 2006).

TRAVGUN was used in combination with a new model developed for this research named “TRAVELLER” (de Vries, 2006) to simulate field level irrigation application. The TRAVELLER model operates by selecting and overlapping the appropriate wind affected wetted patterns for ambient wind conditions from a database generated by the TRAVGUN model. The TRAVGUN-TRAVELLER model can simulate irrigation application using a range of raingun characteristics and management strategies (e.g. raingun make/model, nozzle type/size, water pressure, trajectory angle, sector angle, field orientation relative to prevailing wind, pull speed, pull start times and lane spacing).

Extensive field work carried out in 2003 and 2004 provided the necessary data for calibration and validation of the TRAVGUN-TRAVELLER model. These data demonstrated the application non-uniformity typical of raingun irrigation. Simulations using the TRAVGUN-TRAVELLER model demonstrated an acceptable fit to observed irrigation application data. It was therefore concluded that the TRAVGUN-TRAVELLER model provides a useful tool to simulate the impact of a range of raingun equipment and management strategies on application non-uniformity.

The field level irrigation application patterns generated by the TRAVGUN-TRAVELLER model for a range of equipment and management strategies will be used as inputs to the crop growth modelling stage of the integrated approach. The carrot crop yield and quality models which comprise the crop growth simulation component are presented in the following chapters.

5. Crop growth simulation I: Crop yield model

This chapter presents the selection, parameterisation and validation of the crop yield model. The suitability and data requirements of potential carrot crop yield simulation models are first reviewed and assessed, leading to the selection of a suitable model to fit the research framework. The selected model is then described in more detail. Finally, field data collected for model testing is summarised followed by model calibration and validation.

5.1. Carrot crop yield model selection

5.1.1. Model requirements

In order to evaluate the effect of a range of equipment and management strategies on raingun non-uniformity and the consequences for crop yield and quality, a model capable of simulating carrot crop yield as a result of heterogeneous irrigation was necessary. The requirements of the model are summarised below:

i) The ability to simulate carrot yield using real meteorological data while allowing crop husbandry practices (including irrigation) to be included;

ii) The capability to simulate carrot yield response to spatially and temporally variable soil moisture as a result of irrigation non-uniformity through the growing season;

iii) The facility to handle irrigation application data from the TRAVGUN-TRAVELLER raingun model, and;

iv) The ability to be linked to a crop quality model.

A limited number of crop models have been developed for carrot growth simulation which fall into two categories: generic crop growth models (which have been calibrated for carrots); and carrot-specific models. These are briefly described below along with their data requirements and suitability for the research.

5.1.2. Generic crop growth models

The generic crop growth model SUCROS 87 was parameterised for carrots by de Visser *et al.* (1995). However, Krzesinski and Knaflewski (2004) noted that the model showed large deviations in simulated crop yield from observed data, primarily as a result of problems with model calibration. The limited validation and data requirements for calibration meant that this model was therefore not considered suitable for this research.

A second generic crop growth model, STICS (Brisson *et al.*, 1998; 2002; 2003), has also been parameterised and used for a number of crops such as maize (Bruckler *et al.*, 2000; Lafolie *et al.,* 2000; Ruelle *et al.*, 2003), wheat (Cemagref, 1999; Rodriguez *et al.*, 2004) and carrots (Bourgeois and Gagnon, 2001). STICS is a relatively complex Windows™ based model which requires large amounts of input data (crop growth characteristics, husbandry, soil and climate) and generates a comprehensive output for each model run. However, it is not currently capable of batch processing data. Despite these operational drawbacks, STICS has been used in combination with irrigation models, such as the Grose (1999) model as part of NIWASAVE (Cemagref, 1999). These characteristics therefore made STICS potentially suitable for this work.

5.1.3. Carrot-specific models

Carrot-specific models focussing mainly on the effects of sowing density and competition on crop growth have been developed in the UK by Benjamin and Sutherland (1992), Aikman and Benjamin (1994) and Benjamin and Reader (1998). Similarly, Li *et al.* (1996) created a density and nutrient dependent model for carrot growth and root size using glasshouse experiments. In New Zealand, Reid and English (2000) developed a relatively simple mechanistic model for potential carrot growth. However, all of these models assume a non-limiting water supply, and are therefore not suitable for this research.

Krzesinski and Knaflewski (2004) developed a radiation use efficiency model for carrot growth in Poland which included a function to account for the effect of soil water potential on yield. This required relatively simple crop characteristic and climate input data. However, the trials used for model calibration featured no variations in irrigation inputs; hence it is likely that the soil water function may be somewhat limited in range. Furthermore, the model did not incorporate a soil water component (although it would have been possible to incorporate this aspect) and the model was not readily available for research purposes. This model was therefore not selected for this research.

Reid (2005a) developed a Windows™ based model (termed the "Carrot Calculator") for industry use in New Zealand. This model is based on the potential growth model of Reid and English (2000) coupled with a simple soil water balance model derived from Ritchie (1972), Richardson and Ritchie (1973) and Ritchie (1981a,b), and a model which modifies potential yield responses according to plant density, soil water and nutrient status (PARJIB – Reid, 2002; Reid *et al.*, 2002). The model has been calibrated for two common processing carrot varieties and readily allows input of soil characteristics, daily climatic data and crop husbandry practices (including irrigation). A modified version of the model has also been constructed which allows batch processing of a large number of irrigation input data files (Reid, 2005b). These features made the Carrot Calculator potentially suitable for this research.

5.1.4. Summary and model selection

Following the above critical evaluation of the potential crop yield models, it was apparent that two models could have been appropriate for this research; namely the STICS model and the Carrot Calculator model.

STICS has been used for a number of crop simulations in combination with irrigation simulation models. However, it is a complex model which requires a large amount of input data, generates excessively large outputs and cannot process multiple irrigation data. These operational difficulties limit the applicability of STICS for this particular type of research.

On the other hand, the Carrot Calculator model has been designed and tested for application in industry, requires considerably less input data and has the ability to batch process irrigation data. The model functions mechanistically, allowing simulation of crop growth under any climate. The Carrot Calculator model would therefore allow simple and efficient simulation of carrot yields in response to spatially variable irrigation data generated by the raingun model.

At the outset of this research, the Carrot Calculator model was not available, therefore a decision was made to use STICS and an attempt was made to modify it for use in generating spatial variations in carrot yield as a result of irrigation non-uniformity. However, as noted above, there were considerable difficulties in using STICS for this research. Therefore, STICS was subsequently rejected in favour of the batch processing version of the Carrot Calculator model when it became available in 2005. It should be noted that soil and crop growth field data was originally collected for use in calibrating and validating STICS rather than the Carrot Calculator, leading to some limitations in operation of the latter model. However, it was considered that the benefits of using this model outweighed the drawbacks of the limited dataset. A computer program was developed to convert the field-level irrigation application outputs from the TRAVGUN-TRAVELLER model into the required format for the Carrot Calculator model (Appendix B). The Carrot Calculator model is described in more detail below.

5.2. The Carrot Calculator model

The Carrot Calculator (Reid, 2005a,b) is a relatively simple mechanistic carrot growth model with a Windows™ based graphical user interface. It was initially designed as a tool to assist New Zealand carrot growers in making informed crop management decisions. These included, for example, when to sow and at what density; what nutrient and irrigation regime is likely to be necessary; and when to harvest for a desired root size (Reid, 2005a). Consequently, the program was designed to be simple to use requiring only minimal input data. A modified version of the model, capable of batch processing a number of simulations (differing in terms of irrigation input) has been developed for use in this thesis (Reid, 2005b).

There are three main components to the Carrot Calculator model:

i) a potential yield model for carrot growth under non-limiting conditions;

ii) a simple soil water balance model, and;

iii) a model termed "PARJIB" which modifies potential yield according to plant density, water and/or nutrient limitations.

A brief description of each component and their calibration and validation is given below.

5.2.1. Potential yield component

A detailed description of the carrot potential yield model, its calibration and validation is presented in Reid and English (2000). A brief overview is provided here.

The model is driven by two environmental variables – daily mean air temperature (°C) (derived from daily minimum and maximum temperatures) and daily total incident radiation (MJ m^{-2}). Crop emergence is determined as a function of thermal time. From emergence, two growth stages are distinguished – Stage 1 where growth is not limited by competition from neighbouring plants and Stage 2 where competition reduces the leaf expansion rate and causes the canopy light extinction coefficient to vary with plant density. Green leaf area index (LAI) is calculated on a daily time-step driven by mean air temperature weighted for suitability for leaf expansion. Leaves grown on any given day are assumed to senesce and no longer contribute to photosynthesis after a fixed period of thermal time. The proportion of incident radiation intercepted by the canopy is dependant on the green leaf area index and the canopy light extinction coefficient. Dry matter accumulation is assumed to be directly proportional to light interception based on a Beer-Lambert Law analogue. The partitioning of dry matter to shoots and storage roots is assumed to be dependant on the degree to which the canopy has attained its maximal green leaf area index. Storage root fresh weight is then calculated from dry weight using a simple empirical function.

Reid and English (2000) report that data for calibration were taken from randomised block experiments carried out in 1997/8 at the Hawkes Bay Research Centre of the New Zealand Institute for Crop and Food Research, near Hastings in the North Island. Leaf area, root fresh mass, root dry mass and shoot dry mass were measured at intervals through the season from replicate plots sown at different densities for two processing carrot varieties – Red Hot and Chantenay Red Core. The calibrated model accounted for between 60% and 88% of the observed variation in leaf area, shoot and root dry mass, root fresh mass and yield.

The model was validated with further experimental data from Hawkes Bay, carried out in 1995/6 and 1996/7. Root fresh mass, root dry mass and shoot dry mass were measured at intervals through the season from replicate plots sown at three dates (early spring, late spring and early summer) at a different density in 1995/6 to 1996/7, again using the varieties Red Hot and Chantenay Red Core. Pooling both experiments together, the model accounted for 68% and 60% of the observed variability in yield for Chantenay Red Core and Red Hot varieties respectively (Reid and English, 2000).

5.2.2. Soil water balance component

The soil water balance component of the Carrot Calculator model is based on the simple energy budgeting approach of Ritchie (1972), Richardson and Ritchie (1973) and Ritchie (1981a) using a soil evaporation component as described in Reid (1990) and a soil drainage component similar to Ritchie (1981b). A full description of the model is provided by the authors and is briefly summarised below.

Daily soil water content is calculated using a simple balance of soil evaporation, crop transpiration, precipitation/irrigation and drainage (Richardson and Ritchie, 1973).

Soil evaporation is determined as the smallest value of a maximum soil evaporation rate which is primarily dependant on the radiant energy input to the soil (Ritchie, 1972), and a soil evaporation rate for drying soil surface conditions. The latter of these is derived in Reid (1990) from Boesten and Stroosnijder (1986). It determines soil evaporation from an empirical constant which relates to the water transmission characteristics of the soil and the cumulative soil evaporation minus (rainfall + irrigation) since the last soil re-wetting.

Under non-limiting water conditions, plant transpiration is directly related to reference evapotranspiration (ET_o) and the fraction of incident light that is intercepted by the canopy (calculated from leaf area index). However, above a threshold soil water deficit, the fraction of actual transpiration over the non-limited value is reduced linearly with increasing soil moisture deficit, reaching zero when the latter is equal to the soil's available water capacity (Ritchie, 1981a).

Drainage occurs from the soil profile when the soil water content exceeds field capacity, decreasing logarithmically with time using a modified version of the drainage component in Ritchie (1981b) (Reid, *pers. comm.* 2006). The model does not account for runoff – it assumes infiltration of all water applied to the soil. This is a reasonable assumption for UK conditions where carrots are typically grown on light, free-draining soils with high infiltration rates.

The approach of this simple soil water balance model is widely accepted and has been used and validated (in various slightly modified forms) in other crop growth models such as the DSSAT suite of models (Jones *et al.*, 1998; 2003) and the CERES suite of models (Ritchie and Otter, 1985). It is therefore assumed that this soil water balance approach provides a reasonable simulation of soil water movement within the Carrot Calculator model.

5.2.3. PARJIB component

A detailed description of the PARJIB model for limiting potential yield due to plant density, soil water and nutrient conditions is presented in Reid (2002). A brief summary is given below.

The model calculates yield response to nutrient supply based on maximum yield, which is determined as the potential yield (driven by cultivar and climate) adjusted for planting density and water stress. The plant density adjustment is calculated as a multiplier (range 0-1) to the potential yield which is related to the proportion of the planting density to a defined standard population (usually the industry standard) (Reid, 2002). Water stress is also calculated as a multiplier (range 0-1) to the potential yield, based on the Penman or "Active ET" model as described in Penman (1970), French and Legg (1979) and Jamieson *et al.* (1995). The value of this multiplier remains 1 unless the maximum potential soil water deficit (defined as the maximum value of daily potential evapotranspiration minus (rainfall + irrigation)), exceeds a critical value. Above this threshold, the value of the multiplier is reduced in relation to the degree of stress experienced and the cumulative potential evapotranspiration (Reid, 2002). The effect of nutrient supply on yield is related to the proportion of nutrients available compared to the optimum nutrient supply required to achieve maximum yield (after adjusting potential yield for density and water stress). The effects of more than one nutrient on yield are combined in a simple equation (Reid, 2002).

The PARJIB model was calibrated and validated by Reid *et al.* (2002) using data for five varieties of maize grown under a wide range of conditions in New Zealand from

1996-1999. After calibration using a single variety, the model accounted for 66-73% of the observed variation in yield for all the other data.

PARJIB was also calibrated and validated for three processing carrot varieties (Red Hot, Chantenay Red Core and Koyo) using data from experiments designed to quantify carrot response to water and nutrient stress (Reid, 2005a; Reid *et al.*, 2005). The experiments were carried out in three locations in New Zealand - Lincoln (South Island), Ohakune and Hastings (North Island) and covered a range of planting arrangements and densities, soil types and water/nutrient regimes. The fitted model was reported to account for 84% of the observed variability in root yield.

5.2.4. Data requirements and outputs

The Carrot Calculator model requires data inputs relating to crop husbandry, soil characteristics (chemical and physical), climate, fertiliser regime and irrigation regime (Table 5.1). Crop husbandry, soil characteristics and fertiliser regime data are entered directly via the user interface whereas climate and irrigation data are prepared externally as text files.

In its standard mode, the Carrot Calculator performs single simulations of crop growth when any of the input data are changed. Outputs are presented graphically in the user interface and can then be exported in a separate file. In the batch processing mode used for this study, the processing of multiple simulations is initiated by the selection of more than one irrigation file. Each irrigation file describes the irrigation applications (date and depth applied) through the season to a defined area. For this study, this relates to each 5 m x 5 m study plot at the field sites or each plot within the 5 m grid spacing in the irrigation application outputs from the TRAVGUN-TRAVELLER model. A total of 2047 files can be processed in a single batch run.

In the batch processing mode, the Carrot Calculator model generates outputs for a selected day after sowing (DAS) which are reported in a text file. This file contains scenario and irrigation file names, DAS, fresh root yield (t ha^{-1}), dry root yield (t ha^{-1}), cumulative rain and irrigation (mm), cumulative potential crop evapotranspiration (mm), cumulative actual crop evapotranspiration (mm), cumulative soil evaporation (mm) and cumulative drainage (mm).

Table 5.1 *Summary of the Carrot Calculator model data input requirements.*

Crop husbandry	**Soil chemical**	**Soil physical**	**Climate**	**Fertiliser regime**	**Irrigation regime**
Planting date Variety (Red Hot or Chantenay Red Core) Planting arrangement Emergence (%)	pH Olsen test P (µg cm^{-3}) Extractable Ca, Mg, K, Na (meq 100g^{-1}) CEC (meq 100g^{-1}) Anaerobic incubation test available N (kg ha^{-1}) Laboratory bulk density (g cm^{-3}) Sampling depth (mm)	Field bulk density (g cm^{-3}) Structural score* Available water capacity for whole rooting depth (mm) Drainage class for profile** Soil evaporation constant Presence of water table in upper 1.2 m of profile	Year Julian day Daily minimum temperature (°C) Daily maximum temperature (°C) Daily rainfall (mm) Daily global radiation (MJ m^{-2})	Fertiliser name N, P, K, S, Mg, Ca content by % Fertiliser cost (NZ$ t^{-1}) Application rate (t ha^{-1})	Year Julian day of irrigation(s) Depth of irrigation(s) applied (mm)

* Soil structural score from the New Zealand Recommended Best Management Practice Soil Structure Scorecard (http://www.crop.cri.nz/home/products-services/crop-production/rbmp/maize/FS_S&F_SoilScore.htm)
** Drainage class score from 0-4 where 0 indicates a soil which never exceeds field capacity

5.3. UK field data for parameterisation and validation of the Carrot Calculator

Carrot crop growth data (including soil properties and weather data) were collected from the two field sites in East Anglia (I2003 and R2004) for use in the parameterisation and validation of the Carrot Calculator model. General field site descriptions and sampling plot layout are given in Section 4.3. A specific description of the two field sites relating to the methodology for soil, climate and crop growth data collection is given below followed by a summary of the observed data.

5.3.1. Site I2003

Site I2003 was cultivated in mid- to late-April 2003 and was irrigated pre-drilling with a 25 mm application. The carrot variety “Nerac” was drilled from 28th April to 7th May 2003 (mean date assumed to be 1st May) in two blocks at 185.3 seeds m^{-2} and

173.0 seeds m^{-2} respectively (Figure 5.1). Emergence was assumed to occur 21 days after sowing.

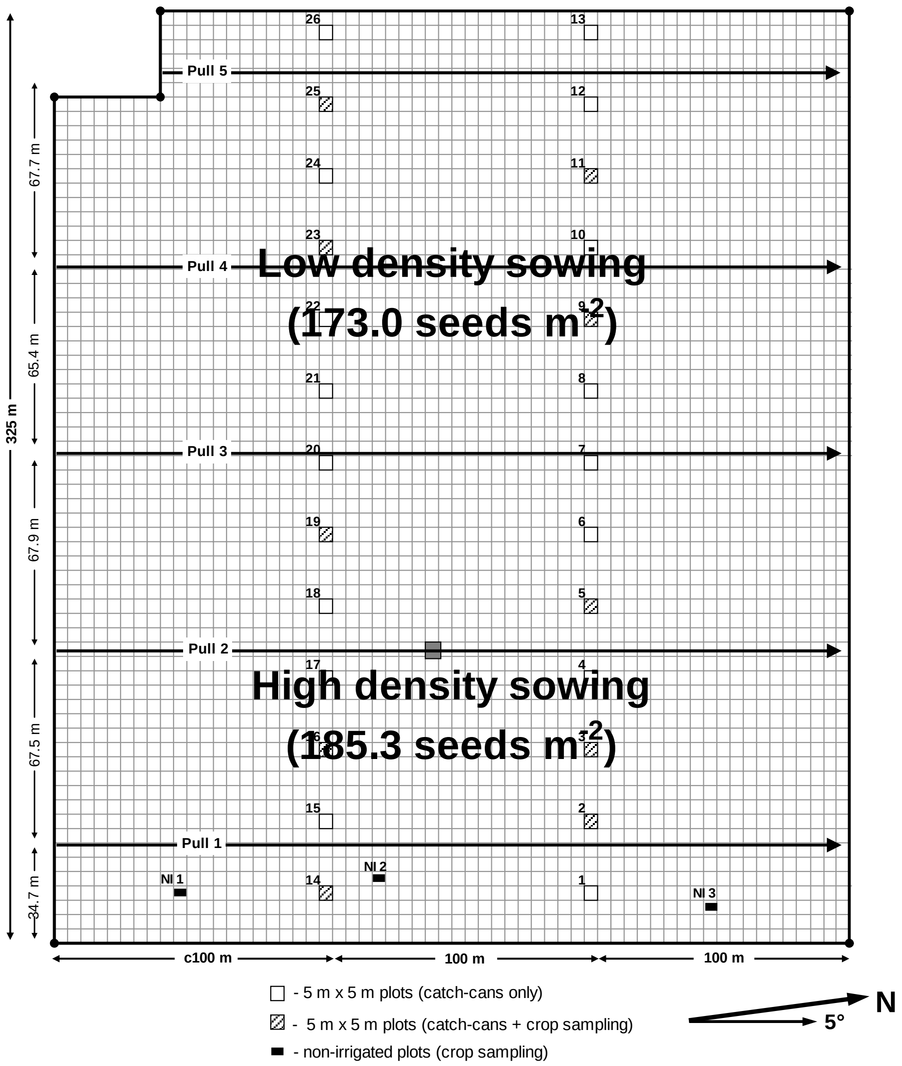


Figure 5.1 *Location of high and low density sown areas in 2003 field site.*

Of the 26 marked study plots, ten were chosen at random to use for crop data collection (plant density, leaf area index, shoot and root dry biomass and final yield) through the season. However, one of these plots suffered from heavy weed infestation early in the season, and was therefore excluded from the dataset. Crop data was also collected from three plots (one bed wide by 2.4 m long) which were sheltered with mobile covers from all irrigation during the season. However, due to leaf scorching from the plastic cover and the likelihood that irrigation water infiltrated into the plots from the wheelings, these data were also excluded. Three of the ten crop study plots were chosen at random for measurement of soil properties.

Seven post-emergence irrigations were applied through the season, with a total scheduled application of 207 mm. The depth of water applied to each plot was recorded using a grid of nine replicate catchcans.

5.3.2. Site R2004

Site R2004 was cultivated in February 2004 and drilled with variety "Nairobi" at 187.4 seeds m^{-2} on the 16th March 2004. Emergence was assumed to occur 21 days after sowing. Figure 5.2 shows a typical carrot bed 56 days after sowing.

Figure 5.2 *A typical carrot bed 56 days after sowing at site R2004.*

Of the 24 marked study plots, three were sheltered using mobile covers for part of each application (denoted "semi-irrigated", SI) and a further three were covered for all irrigations ("non-irrigated", NI). Crop data (plant density, leaf area index, shoot and root dry biomass and final yield) were collected from five fully irrigated (FI) plots and all the SI and NI plots. Four of the crop study plots were chosen at random to determine soil properties using soil pits. Aggregated surface soil samples were taken from all the study plots.

Six irrigations were applied through the season, with a total planned application of 150 mm. The depth of water applied to each of the study plots was measured using catchcans.

5.3.3. Soil properties

Soil pits were dug to a depth of 1.1 m (where possible) in each of the soil study plots at both field sites. The soil profile was described including the horizon thickness (horizons A, B and C), obstacles to rooting and rooting depth. Figure 5.3 shows example soil profiles from both field sites.

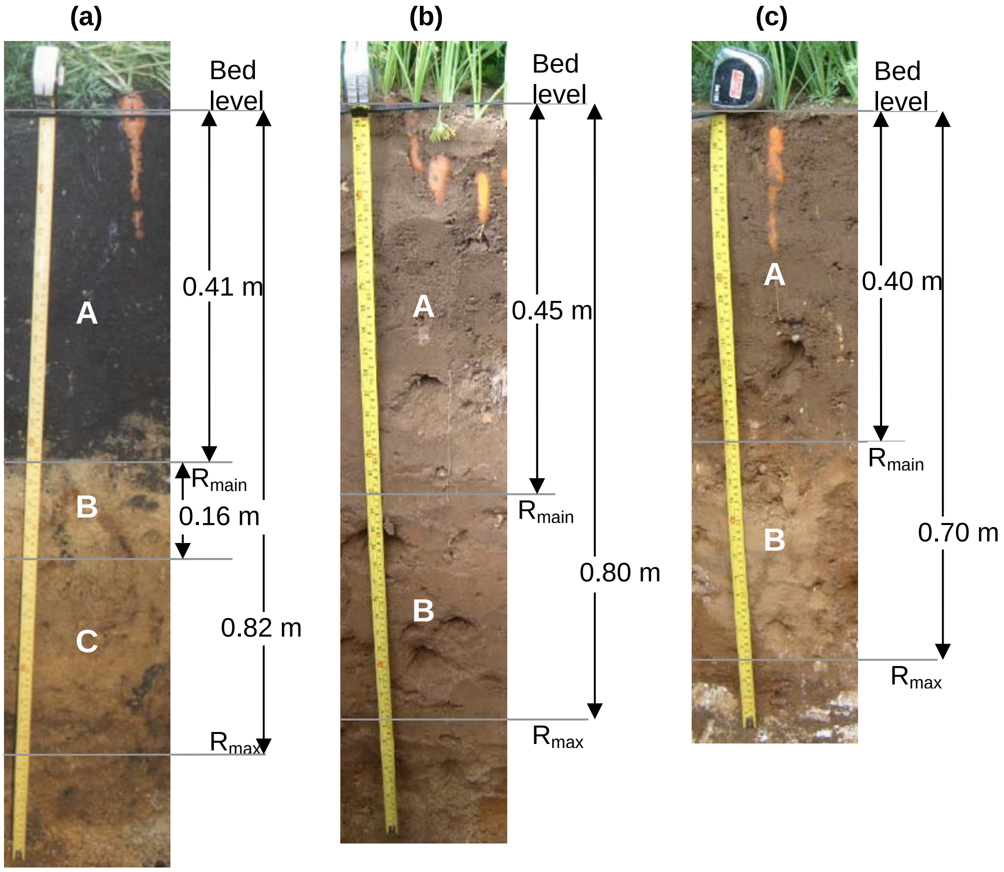


Figure 5.3 *Example soil profiles at site I2003 (a) and site R2004 (b, c), showing main horizons (A, B and C), main rooting depth (R_{main}) and maximum rooting depth (R_{max}).*

The soil at site I2003 was a humose sandy clay loam (horizon A) over a compacted coarse gravely sand with occasional clay lenses at depth (horizon C). In most cases, there was an intermediate mixed layer (horizon B) between these horizons. The soil has the characteristics of the Isleham series, tending towards the Adventurers' series (Hodge *et al.*, 1984). The majority of carrot roots were found in the topsoil (mean depth of 0.44 m), although a few roots were observed extending to a mean maximum depth of 0.83 m.

The soil at site R2004 was a loamy sand bordering on sand (horizon A) over a coarse sand (horizon B), with irregular outcrops of chalky marl rising to c0.7 m below the surface (Figure 5.3c). The soil has the characteristics of a well cultivated Worlington series (Corbett, 1973). The majority of carrot roots were found in the topsoil (mean depth of 0.42 m), with a few roots extending to a mean maximum depth of 0.81 m.

Two replicates of 100 mm diameter (Ø) by 130 mm long cores were taken from the main horizons (A, B and C) at each site to calculate bulk density (Campbell and Henshall, 2001), saturated hydraulic conductivity by falling head permeameter (Youngs, 2001) and stone content (stones >2 mm). A further three replicates (two in 2003) of 51 mm Ø by 19 mm long cores (54 mm Ø by 20 mm long in 2003) were removed to determine water content at saturation, field capacity (-5 kPa) and permanent wilting point (-1.5 MPa) using a sand table (Smith and Thomasson, 1982) and pressure membrane (Richards, 1947; Salter and Haworth, 1961).

Table 5.2 presents a summary of the soil horizon properties for both field sites. Soils at both sites had a relatively large amount of available water and similar stone contents. The peaty fenland topsoil (A) at the 2003 site had a low bulk density and was relatively free draining compared to the subsoil horizons (B and C). At the 2004 site, both topsoil (A) and subsoil (B) had a similarly high bulk density and were free draining, with the topsoil having a particularly high hydraulic conductivity.

***Table 5.2** Summary of soil properties by horizon at sites I2003 and R2004.*

Site	Horizon	Bulk density (g cm^{-3})	Hydraulic conductivity (m d^{-1})	Stones (% by mass)	Water content (% by volume) at:			
					Saturation	Field capacity	Permanent Wilting Point	Available water
I2003	**A**	0.90	1.51	5*	70.9	40.5	22.2	18.3
	B	1.44	0.66	5*	47.4	21.6	8.3	13.3
	C	1.59	0.22	10*	48.4	20.0	8.5	11.5
R2004	**A**	1.47	4.95	6.2	51.2	22.4	6.8	15.6
	B	1.64	1.52	8.5	46.5	26.6	9.5	17.1

* Stone content at 2003 site is an estimated value.

From each of the soil study plots at sites I2003 and R2004, ten random trowels of surface soil (to 0.1 m depth) were aggregated into one sample. These were analysed for ammonium content (ADAS, 1986), total oxides of nitrogen (TON) (ADAS, 1986), mineral particle size fractions (British Standards Institution, 1990a), organic matter by loss on ignition (British Standards Institution, 1990b), calcium carbonate ($CaCO_3$) content (Hodgson, 1997) and pH (British Standards Institution, 1990b)[4].

Table 5.3 presents a summary of the surface soil properties for both field sites. Note that ammonium and TON values were very low at both sites, thought to be a result of leaching from the surface soil. This data was therefore not used for modelling purposes. The fenland surface soil from site I2003 had a high organic matter content with relatively high proportions of sand and clay, little $CaCO_3$ and a neutral pH. The surface soil from the site R2004 had very little organic matter, with a high proportion of sand, a moderate amount of $CaCO_3$ (from the chalk bedrock) and a slightly alkaline pH.

Table 5.3 *Summary of surface soil properties at sites I2003 and R2004.*

Site	**Mineral content (% by mass of total mineral content)**			**Organic matter content (% by mass)**	**$CaCO_3$ content (% by mass)**	**pH**	**Ammonium (mg kg^{-1})**	**TON (mg kg^{-1})**
	Sand	**Silt**	**Clay**					
I2003	70.8	11.4	17.8	18.3	1	7.0	0	1.8
R2004	85.7	8.8	5.4	1.5	5	7.7	0	0.6

5.3.4. Climate data

Climate data was collected from automated meteorological stations located c0.7 km and c2.5 km from sites I2003 and R2004 respectively. The available data (recorded at 15 minute intervals) was air temperature (°C), relative humidity (%), rainfall (mm), wind speed (m s^{-1}), wind direction (°) and short-wave global radiation (MJ m^{-2}). Rain gauge data from site R2004 (located c1 km from the field) were also obtained where possible to supplement this data. Climate data were obtained for the period 1998-2004 at site I2003 (denoted I1998-I2004 for clarity) and for the period 1999-2004 at site R2004 (denoted R1999-R2004). The raw data was processed using the AWSET program (Cranfield University, 2002) to produce daily average values for the key climate

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[4] Note that soil analysis was carried out to gain data for the STICS crop model; model choice was revised in favour of Carrot Calculator after the data collection period owing to non-suitability of STICS for the research. Therefore some of the soil parameters required for the Carrot Calculator were not recorded.

variables including daily reference evapotranspiration (ET_o) based on the Penman-Monteith method. Any missing data were replaced by data from the nearest available weather station.

Figure 5.4 summarises the climate at site I2003 for the study period. Mean daily temperature during the growing season (from sowing on 1st May to straw mulching on 1st October) was 16.2°C, ranging from 7.9-26.7°C. Total precipitation for the year was 443 mm, of which 174 mm fell during the growing season. Daily ET_o during the growing season ranged from 0.9-4.9 mm d^{-1}, with a seasonal mean of 2.8 mm d^{-1}. The total planned irrigation application during the growing season was 207 mm over 8 irrigation events. Irrigations were scheduled by the grower, typically based on visual crop and soil assessment and broadly following the potato irrigation regime on the farm.

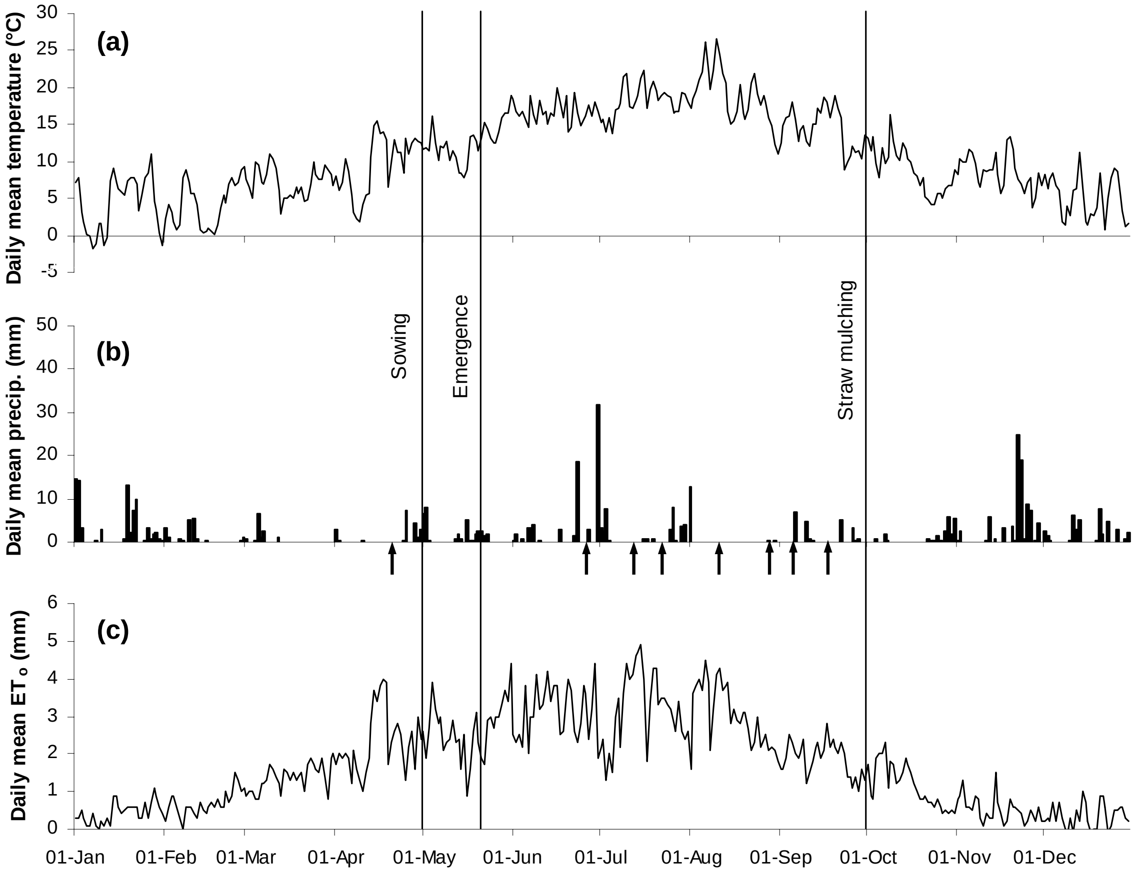

Figure 5.4 Mean daily temperature (a) precipitation (b) and ET_o (c) at site I2003. Arrows indicate the timing of individual irrigation events.

Figure 5.5 summarises the climate at site R2004 for the study period. Site R2004 was generally cooler than site I2003 during the growing season (from sowing on 16th March to harvest on 16th September), with a mean daily temperature of 14.2°C, ranging from 4.5-21.8°C. Precipitation at site R2004 was greater than site I2003 with a total of 799 mm, of which 371 mm fell during the growing season, the majority falling early and late in the season. Daily ET_o during the growing season was lower at site R2004 than at site I2003, ranging from 0.5-3.9 mm d^{-1}, with a seasonal mean of 2.2 mm d^{-1}. The total planned irrigation application during the growing season was 150 mm over 6 irrigation events. Irrigations were scheduled using soil moisture monitoring and advice from a contracted service.

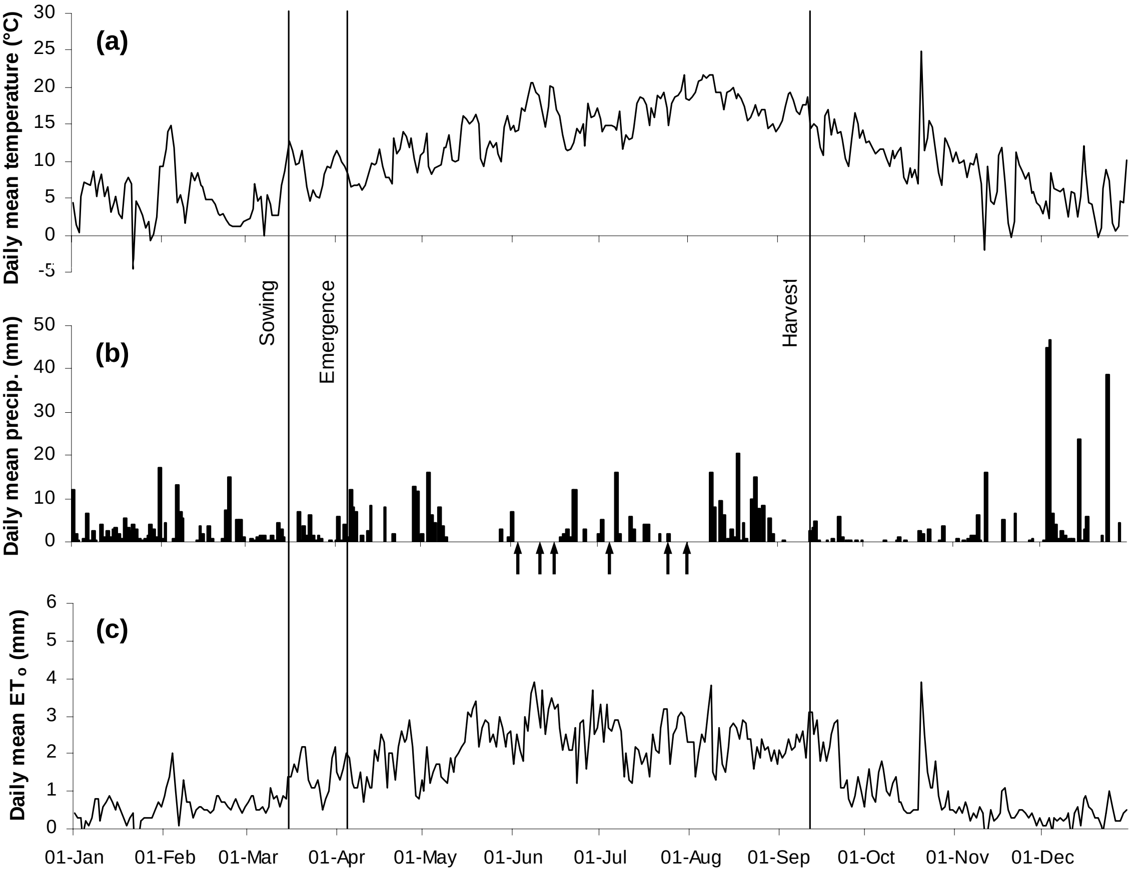

Figure 5.5 *Mean daily temperature (a) precipitation (b) and ET_o (c) at site R2004. Arrows indicate the timing of individual irrigation events*

As an indication of the comparative "dryness" of the 13 years of available climate data, the maximum potential soil moisture deficit ($PSMD_{max}$) was calculated (i.e. the maximum value of daily potential evapotranspiration minus rainfall) (Figure 5.6). Note that $PSMD_{max}$ used here as an indicator of climatic conditions differs from that in Section 5.2.3, where it is used as an indicator of the drought stress experienced by a crop (i.e. daily potential evapotranspiration minus (rainfall *plus* irrigation)).

It can be seen from Figure 5.6 that the climate at site I2003 was particularly dry, whereas R2004 was more typical over the recorded data period. Interestingly, despite the proximity of the field sites (within 35 km of each other), considerable climatic differences were observed between them. The $PSMD_{max}$ was generally higher at site I2003 than at R2004. This was most likely due to differing rainfall patterns in the region – for example I1999 received a total annual rainfall of 612 mm whereas R1999 received 603 mm, but I2002 received only 429 mm compared to 623 mm at R2002. In addition, some of these climatic variations between sites may also reflect differences in data integrity between the two meteorological stations.

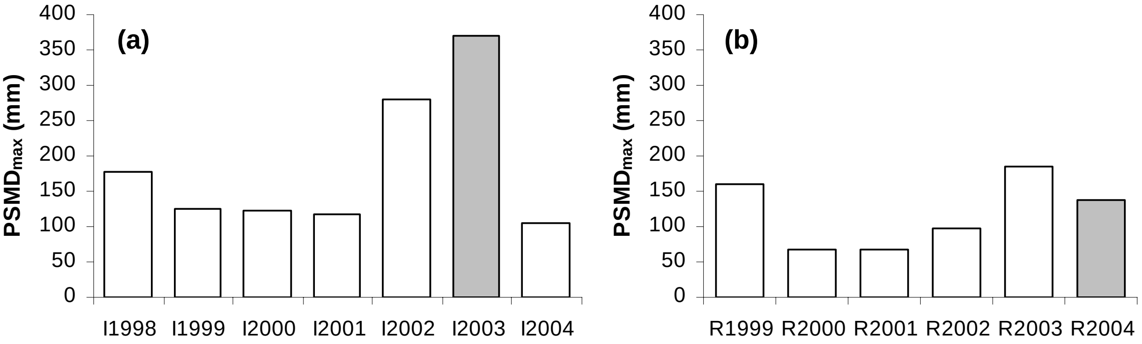

Figure 5.6 *Maximum potential soil moisture deficit ($PSMD_{max}$) (not including irrigation) for I1998-I2004 (a) and R1999-R2004 (b). Shaded columns indicate field study years.*

5.3.5. Crop growth data – plant density, leaf area index and biomass

At site I2003, three randomly placed replicate whole carrot samples were removed from each of the crop growth plots at approximately fortnightly intervals (2nd, 15th, 29th July, 14th August and 2nd ,29th September 2003). Each sample was 0.3 m long by one triple row of carrots wide, reduced to 0.15 m long from 14th August onwards. Plant density was calculated from the samples and leaf area index (LAI)[5] in m^2 leaf per m^2 ground was measured using digital image analysis. Shoot and root dry biomass was measured at

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[5] LAI data were originally collected for use in the STICS crop model. The Carrot Calculator model which subsequently replaced STICS did not require LAI data. However, the data have been included here for interest.

three sampling dates (15th July, 2nd and 29th September 2003) by oven drying at 60°C for a minimum of 48 hours.

At site R2004, three whole carrot samples were removed from each of the crop growth plots at approximately fortnightly intervals (6th,18th June, 7th,28th July, 12th August and 7th September 2004). Each sample was 0.2 m long by one triple row of carrots wide. Plant density and LAI were calculated as at site I2003. Shoot and root dry biomass was measured at four sampling dates (6th June, 7th July, 12th August and 7th September 2004).

Plant density

Mean plant density at site I2003 was 129.1 plants m^{-2} in the area sown at the lower density and 141.5 plants m^{-2} in the higher density area, giving an average establishment rate of 76%. An analysis of variance showed that the difference in plant density between the two blocks was significant[6]. At site R2004 the mean plant density was 114.3 plants m^{-2}, giving an average establishment rate of 61%. Although there was relatively large variability in the density data collected at this site, analysis of variance indicated that there were no significant differences in density between irrigation treatment plots or sampling dates. Establishment was thought to be relatively low and variable as a result of a sub-optimal seed-bed.

Leaf area index

A summary of LAI development at site I2003 is presented in Figure 5.7. Typically for carrots, the early leaf development rate was slow until about 60 days after sowing (DAS). Hereafter, canopy expansion was rapid, reaching a maximum LAI of about 5 m^2 m^{-2} at approximately 110 DAS before declining slightly to harvest. A similar LAI development profile was recorded by Bourgeois and Gagnon (2001) for a crop grown in Canada (Figure 3.6a). However, their crop exhibited the rapid expansion phase much earlier (about 40 DAS) and achieved a greater LAI of around 6 m^2 m^{-2}. These discrepancies were most likely due to differences in climate, variety and crop husbandry.

An analysis of variance showed that despite the relatively large amount of variability in the data, there were no significant differences in LAI between plots in all but one of the

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[6] all significance levels are given at $p \geq 0.05$

sampling dates. There were also no significant differences in LAI between the two areas sown at different densities.

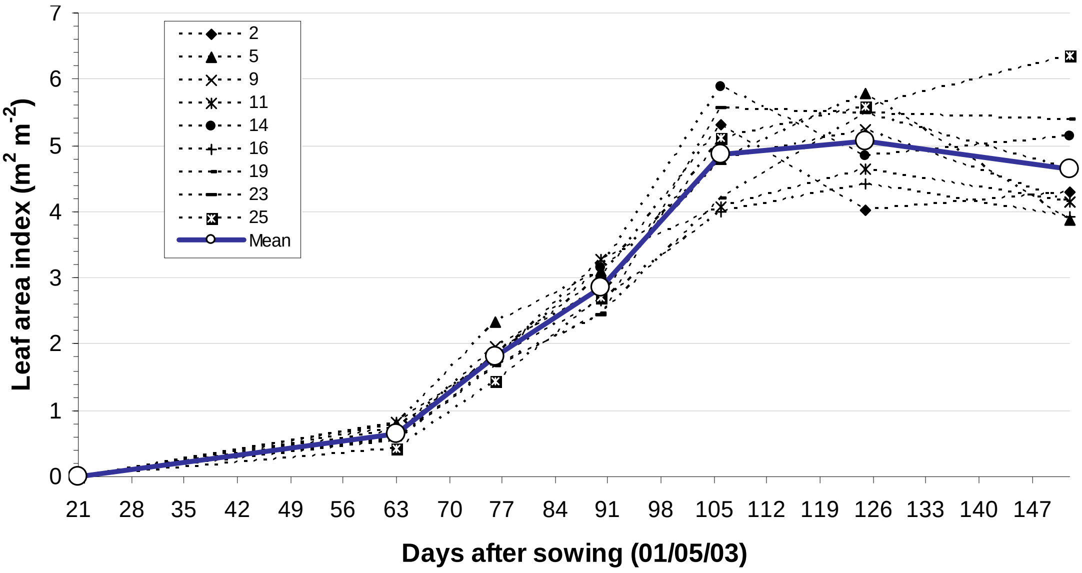

Figure 5.7 *LAI development at site I2003 for all study plots, showing mean values.*

A summary of LAI development in fully irrigated (FI), semi-irrigated (SI) and non-irrigated (NI) plots at site R2004 is presented in Figure 5.8. Leaf area growth was slow until about 80 DAS, then expanded rapidly to a maximum at about 130 DAS of approximately 3.4 m^2 m^{-2}, 3.3 m^2 m^{-2} and 2.7 m^2 m^{-2} (for FI, SI and NI plots respectively) before declining slightly to harvest. Although the pattern of LAI development was similar to that observed at site I2003, the timing of rapid canopy expansion was slightly later and the maximum LAI attained was lower at site R2004. These differences were most likely due to differences in climate, variety and crop husbandry.

Again, an analysis of variance showed that there were no significant differences in LAI between plots within each irrigation regime. There was a slight trend to suggest that LAI was lower in the NI plots than in the SI and FI plots (Figure 5.8d). However, this trend was not statistically significant. This was most likely due to the relatively large degree of variability in the data as a result of the relatively small size of the samples. In addition, high rainfall in August was likely to have smoothed out any differences in LAI which were developing during the drier part of the season.

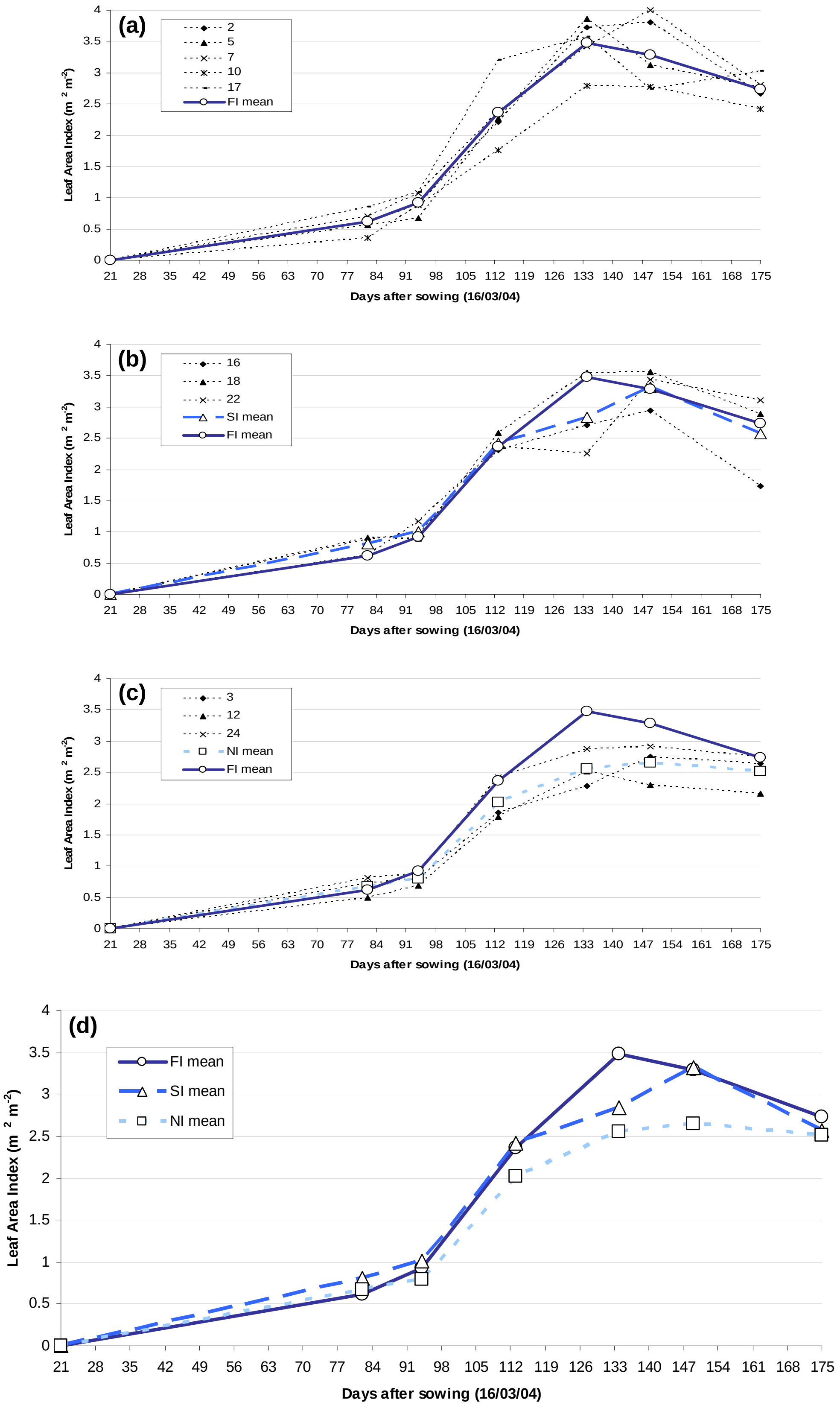

Figure 5.8 *LAI development at site R2004 for FI plots (showing FI mean) (a), SI plots (showing FI and SI mean) (b), NI plots (showing FI and NI mean) (c) and mean LAI for all three irrigation regimes (d).*

The slight decrease in LAI with droughting observed in these results was supported by research in Canada. For example, Caldwell *et al.* (2001) observed that the leaf area of young carrots in growth cabinets decreased with increased periods of droughting. Stiles (2002) also observed that leaf development of carrots in the field decreased with decreasing soil moisture.

Shoot and root dry biomass

The development of shoot and root dry biomass at site I2003 is presented in Figure 5.9. Shoot dry biomass followed a similar development trend to canopy expansion, attaining a maximum of approximately 3.3 t ha^{-1} at about 120 DAS. Typically for a carrot crop, root development showed a slight delay after leaf expansion, with rapid growth occurring from about 80 DAS. Root dry biomass attained a maximum of approximately 9.8 t ha^{-1} by about 120 DAS and generally remained constant until harvest. Root growth data observed by Bourgeois and Gagnon (2001) showed a similar profile, with a rapid root biomass increase occurring about 20 days after the rapid increase in canopy and attaining a maximum dry biomass of approximately 10 t ha^{-1} at about 130 DAS (Figure 3.6b).

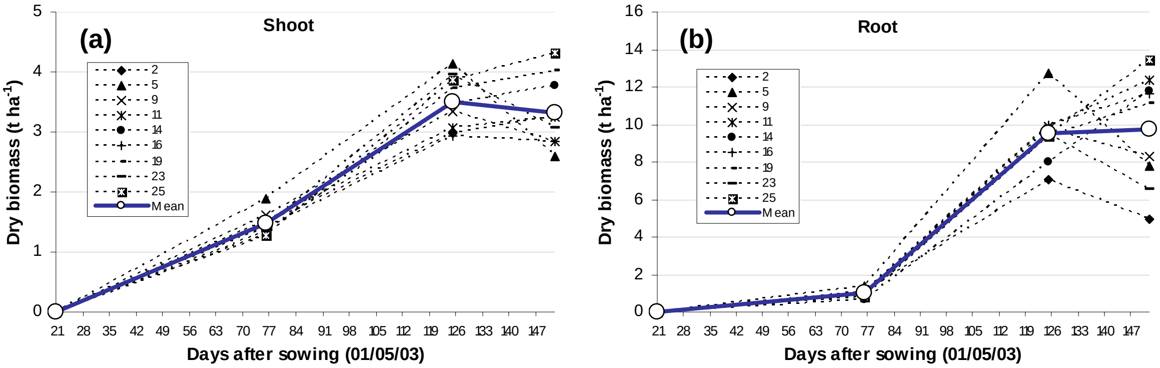

Figure 5.9 *Development of shoot (a) and root (b) dry biomass at site I2003 site for all study plots, showing mean values.*

Although there was a relatively large amount of variability in the data (again mostly due to the small size of the samples), an analysis of variance showed that there were no significant differences in shoot or root dry biomass between plots (except at the last sampling interval). Again there were no significant differences in biomass between the two areas sown at different densities.

Overall mean shoot water content at site I2003 was 82% and mean root water content was 90%.

The development of shoot and root dry biomass in FI, SI and NI plots at site R2004 is presented in Figure 5.10. Shoot biomass growth was again similar to LAI, being slow to about 80 DAS, then increasing rapidly to a maximum at about 150 DAS of 2.7 t ha^{-1}, 2.6 t ha^{-1} and 2.2 t ha^{-1} (for FI, SI and NI plots respectively) before declining slightly to harvest. Root growth showed a slight delay in rapid expansion, occurring about 10 days after rapid shoot expansion. Root dry biomass growth continued through the season, attaining a maximum of approximately 12.3 t ha^{-1} (FI), 10.4 t ha^{-1} (SI) and 9.2 t ha^{-1} (NI) at harvest (175 DAS). However, it was observed that in the three weeks prior to harvest, the root growth rate slowed considerably more in NI plots than either the FI or SI plots.

An analysis of variance showed that there were no significant differences in shoot or root dry biomass between plots within each irrigation regime in all but one instance. There was a trend to suggest that the droughted plots exhibited lower shoot and root biomass than FI plots. However, this trend was not statistically significant at most sampling dates. Again this was likely to be due to variability within the data and the effect of high rainfall at the end of the season.

Although no statistically significant relationship between drought levels and reduced shoot and root growth was observed in this study, many other researchers have found a strong link (reported in Section 3.5.4).

Overall the mean shoot water content at site R2004 was 82% and the mean root water content was 88%.

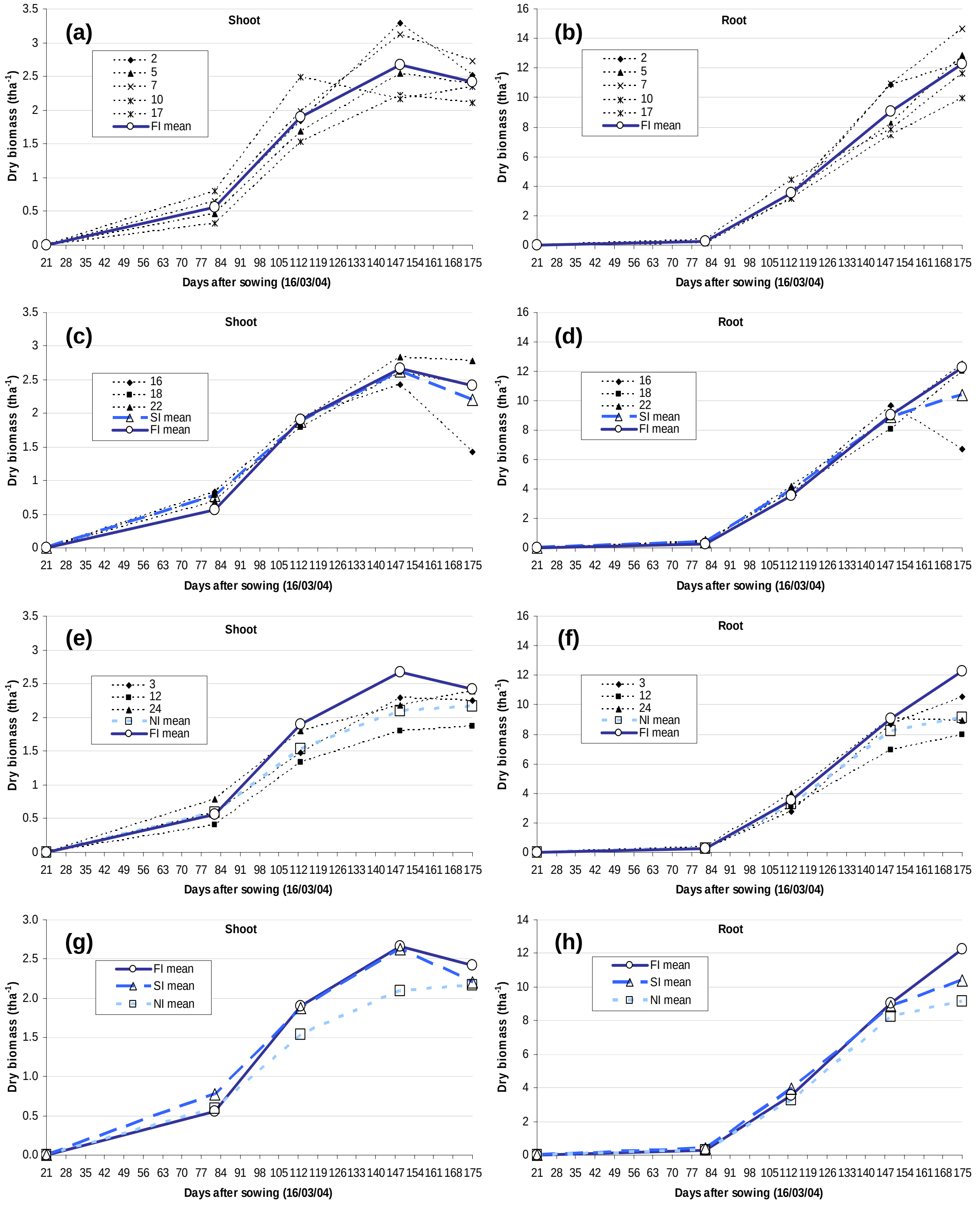

***Figure 5.10** Development of shoot and root dry biomass at site R2004. Shoot (a) and root (b) dry biomass for FI plots (showing FI mean); shoot (c) and root (d) dry biomass for SI plots (showing FI and SI means); shoot (e) and root (f) dry biomass for NI plots (showing FI and NI means); and shoot (g) and root (h) mean values for FI, SI and NI plots.*

5.3.6. *Crop growth data – final yields*

The final yield from site I2003 was calculated from samples taken between the 28th and 30th September, just prior to the field being straw mulched for winter storage. Roots from three 0.2 m wide strips across a bed were removed as a bulk sample. These were washed and dried before grading using approximate industry guidelines[7]. Diseased, fanged, short and other deformed roots (e.g. severely bent, twisted, hairy and green-topped) were removed as waste. The remaining roots were graded into 5 mm shoulder diameter divisions (<10, 10-<15, 15-<20, 20-<25, 25-<30, 30-<35, 35-<40, 40-<45, >45). The roots in each category (including waste) were weighed and counted before the marketable proportion was calculated (non-waste >25 mm in diameter).

The final root yield for each plot at site I2003 is presented in Table 5.4.

Table 5.4 *Summary of final carrot yield data at site I2003 showing graded yield, total yield, marketable yield and marketable percentage for each sample plot, with mean values for high and low density planting areas and overall mean values.*

Grade	**Final yield (t ha^{-1}) for plot:**											
	2	**5**	**9**	**11**	**14**	**16**	**19**	**23**	**25**	**High density area mean**	**Low density area mean**	**Mean**
<10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
10-<15	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
15-<20	0.2	0.4	0.5	1.0	0.2	0.0	0.0	0.5	0.3	0.1	0.6	**0.3**
20-<25	9.4	5.8	4.6	8.0	10.3	3.7	2.7	4.2	5.9	6.4	5.7	**6.1**
25-<30	22.6	32.6	25.4	23.8	43.0	33.1	24.7	13.2	25.3	31.2	21.9	**27.1**
30-<35	34.1	30.7	37.1	42.3	42.2	43.3	41.8	40.5	40.3	38.4	40.1	**39.2**
35-<40	19.2	31.7	26.0	18.7	19.7	23.8	24.9	31.9	21.0	23.9	24.4	**24.1**
40-<45	5.3	6.8	12.8	3.3	5.2	12.6	19.8	16.6	6.8	9.9	9.9	**9.9**
>45	3.7	2.9	4.5	0.0	0.0	1.9	0.0	8.2	0.0	1.7	3.2	**2.4**
Fanged	2.9	3.2	1.8	2.6	5.0	1.1	3.8	8.7	1.8	3.2	3.7	**3.4**
Deformed	20.7	15.6	26.1	22.1	9.1	19.0	15.7	8.3	26.8	16.0	20.8	**18.2**
Short roots	5.5	3.2	1.4	2.3	4.8	1.5	7.3	3.0	4.4	4.5	2.8	**3.7**
Diseased	14.3	0.0	1.8	2.1	0.0	1.2	3.4	1.5	1.8	3.8	1.8	**2.9**
Total yield	**138.0**	**133.0**	**141.9**	**126.3**	**139.3**	**141.3**	**144.1**	**136.6**	**134.5**	**139.1**	**134.8**	**137.2**
Marketable yield	***85.0***	***104.8***	***105.8***	***88.1***	***110.0***	***114.7***	***111.2***	***110.4***	***93.5***	***105.1***	***99.4***	***102.6***
Marketable %	**61.6**	**78.8**	**74.5**	**69.8**	**79.0**	**81.2**	**77.1**	**80.8**	**69.5**	**75.5**	**73.7**	**74.7**

The mean total yield at the site was 137 t ha^{-1}, ranging from 126-144 t ha^{-1}. The area of the site sown at a higher density realised a total yield of about 4 t ha^{-1} greater than the low density area. Mean marketable yield was 103 t ha^{-1}, ranging from 85-115 t ha^{-1}.

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[7] Note that this grading scheme differs to the more representative industry standards defined in Figure 3.7 and used for grading at site R2004.

This resulted in a marketable percentage (or "pack-out") of between 62% and 81% with a mean of 75%. The area sown at a high density realised a marketable yield of about 5 t ha^{-1} greater than the low density area, with a slightly higher marketable proportion. Root size ranged from a shoulder diameter of 15 mm to >40 mm, with the majority falling in the 25-40 mm grades. The majority of waste roots were graded out as a result of excessive deformities.

From this analysis, it was observed that there was less variability in the total yield data than the in root dry biomass final sample – most likely due to the larger sampling size used. However, marketable yield showed a relatively large variability between plots. There was only a small difference in yields between the areas sown at different densities, which was unlikely to be significant given the degree of variability found in the data. No analysis of variance could be performed on the data due to non-replication.

The grower estimated a total "dirty root" yield of 100 t ha^{-1} from the field, with approximately 60% of this being marketable. Dirty root yields are estimated to contain between 5% and 15% soil, depending on soil conditions (Martin, *pers. comm.* 2005; Wright, *pers. comm.* 2005; Hipperson, *pers. comm.* 2005). Assuming a typical soil content of 7% results in a total root yield of 93 t ha^{-1}, with a marketable yield of 60 t ha^{-1} (65%). These estimates are lower than those calculated in this study. This may have been a result of root damage during handling and the top-lifting harvesting technique which tends to leave a relatively large proportion of roots in the field. In addition, the difference between the calculated yields in this study and the grower estimates may have reflected a difference in the grading processes used.

The final yield at site R2004 was calculated from samples taken on the 7th September, prior to harvest. Roots from two 0.2 m wide strips across a bed were taken from each of the eleven study plots as bulked samples. These were washed and graded according to the processor guidelines outlined in Figure 3.7.

The final root yields for FI, SI and NI plots at site R2004 are presented in Table 5.5. Surprisingly, total root yields were higher in the SI plots (110 t ha^{-1}) than FI plots (104 ha^{-1}) with NI plots the lowest (91 t ha^{-1}), but there was a relatively large variability within the results. Marketable yield, however, was greater in the FI plots (81 t ha^{-1}) than either SI plots (74 t ha^{-1}) or NI plots (67 t ha^{-1}). The proportion of marketable roots was lowest in the SI plots and highest in the FI plots. FI plots tended to have more roots in the premium range (20-40 mm) and fewer roots in the market and value grades than SI and NI plots, with NI plots having the smallest amount of high quality roots and the largest amount of low grade roots. FI plots also tended to have the best skin finish and shape, with NI plots the worst. In general, increased droughting appeared to increase root deformities, but had a variable effect on disease levels, scarring, fanging and splitting. Interestingly, plot 5 (which did not receive the first irrigation) was observed to have one of the lowest total and marketable yields of the FI plots and plot 24 (which did receive the first irrigation) had the highest total and marketable yields of the NI plots.

The total root yield at site R2004 reported by the processor was estimated to be 109-165 t ha^{-1} with a marketable yield of 59-71%. The observed yields at site R2004 were slightly lower, but generally with a higher marketable percentage. This may have been due to differences in sampling and grading technique and the occurrence of relatively high levels of cavity spot in some areas of the site which depressed the processor yield estimates.

The reductions in marketable carrot root yields due to water shortages during the growing season observed at site R2004 were consistent with the findings of previous research (reported in Section 3.5.4).

Table 5.5 *Summary of final carrot yield data at site R2004 showing graded yield, total yield, marketable yield, marketable percentage, premium root yield and premium root percentage for each sample plot and mean values for each irrigation regime.*

Grade	**Fully irrigated plots (t ha^{-1}):**						**Semi-irrigated plots (t ha^{-1}):**				**Non-irrigated plots (t ha^{-1}):**			
	2	**5**	**7**	**10**	**17**	**Mean**	**16**	**18**	**22**	**Mean**	**3**	**12**	**24**	**Mean**
>45mm	12.0	4.8	3.6	3.9	12.7	**7.4**	3.7		15.4	**6.4**			6.4	**2.1**
40-45mm	18.9	9.6	2.7	16.1	6.5	**10.8**	15.4	15.2	29.5	**20.0**	6.5	2.7	9.6	**6.2**
30-40mm	54.2	33.0	39.1	38.9	40.1	**41.1**	25.3	33.4	23.0	**27.3**	21.0	27.0	41.5	**29.9**
20-30mm	3.1	12.5	13.6	14.6	3.0	**9.4**	4.5	11.1	7.6	**7.7**	16.2	8.0	6.5	**10.2**
Market	5.8	9.3	13.6	1.2	9.3	**7.8**	6.2	18.0	5.6	**10.0**	13.3	19.5	13.7	**15.5**
Value	1.1	6.9	4.8	5.3	2.5	**4.1**	3.0	1.9	2.3	**2.4**	3.5	2.9	1.8	**2.7**
Outgrade	2.4	2.4	1.7	2.7	2.9	**2.4**	1.0	1.0	2.6	**1.5**	2.6	1.7	3.2	**2.5**
Deformed	2.2	0.8	2.8	0.9	4.2	**2.2**	6.6	5.0	6.4	**6.0**	13.8	10.2	3.0	**9.0**
Severe scar		8.2	10.8	8.7	7.3	**7.0**	16.8	1.6	13.4	**10.6**		3.7	9.2	**4.3**
Fanged		3.9	8.2	1.4		**2.7**	5.2	3.8	1.6	**3.6**	0.4	2.1	1.3	**1.2**
Split	1.5		2.3		6.2	**2.0**		4.1		**1.4**	4.4	4.2	5.0	**4.5**
Scab	3.7		2.2	3.3		**1.8**	9.1	3.3	3.8	**5.4**			3.0	**1.0**
Sclerotina		4.1				**0.8**				**0.0**	3.5			**1.2**
Black rot	2.8	0.4			0.5	**0.7**		5.1		**1.7**	1.1	0.3		**0.5**
Cavity spot			3.8		8.1	**2.4**	8.9	4.4	2.6	**5.3**			1.3	**0.4**
Other	3.0	3.1				**1.2**	0.7		1.3	**0.7**				**0.0**
Skin	av/gd	av/gd	av/gd	av/gd	av/gd	**av/gd**	av/gd	av/gd	av/gd	**av/gd**	av/gd	av/gd	av/gd	**av/gd**
Shape	av/gd	av	av	av	av	**av**	av	av/poor	av	**av**	poor	av/poor	av	**av/poor**
Total yield	**110.6**	**98.9**	**109.1**	**97.1**	**103.2**	**103.8**	**106.5**	**107.9**	**115.2**	**109.9**	**86.3**	**82.3**	**105.3**	**91.3**
Marketable yield	**95.0**	**76.0**	**77.4**	**80.0**	**74.1**	**80.5**	**58.1**	**79.7**	**83.4**	**73.7**	**60.5**	**60.1**	**79.4**	**66.7**
Marketable %	**85.9%**	**76.9%**	**70.9%**	**82.4%**	**71.8%**	**77.6%**	**54.6%**	**73.8%**	**72.4%**	**67.1%**	**70.1%**	**73.0%**	**75.4%**	**73.0%**
Premium yield	**57.3**	**45.4**	**52.7**	**53.6**	**43.1**	**50.4**	**29.8**	**44.5**	**30.6**	**35.0**	**37.2**	**35.0**	**48.0**	**40.1**
Premium %	**51.8%**	**46.0%**	**48.3%**	**55.1%**	**41.8%**	**48.6%**	**28.0%**	**41.3%**	**26.6%**	**31.9%**	**43.2%**	**42.6%**	**45.6%**	**43.8%**

5.4. Parameterisation and validation of the Carrot Calculator model

The Carrot Calculator has previously been calibrated and validated for processing carrots (variety Red Hot and Chantenay Red Core) grown under a variety of soil water and nutrient conditions in New Zealand (Reid and English, 2000; Reid, 2005a; Reid *et al.*, 2005). Data was not available to re-calibrate the model for the Nantes type carrot typically used in the UK. Therefore, to provide confidence in using the model to simulate carrot growth in the UK under differing soil water conditions (due to irrigation non-uniformity) it was necessary validate its performance using the two calibrated varieties. Data collected from the two field sites were used to parameterise the Carrot Calculator model, to provide input data for simulations and to validate the model as described below.

5.4.1. Parameterisation and model inputs

Data relating to crop husbandry, soil characteristics, climate, fertiliser regime, and irrigation were required to parameterise the Carrot Calculator and to provide input data for simulations. It was assumed that the pesticide regime was optimal at both sites. This data is summarised below.

Crop husbandry

The planting dates were defined as 1st May and 16th March for sites I2003 and R2004 respectively. The planting arrangement was determined from in-field measurements at both sites. Both sites used the same row and bed configuration on c2 m wheel centres, with four triple rows of carrots per bed (Figure 5.11).

Mean plant emergence rates were defined from observed data as 76% (I2003) and 61% (R2004). The spacing between plants within a row was estimated from plant density data then modified to result in a plant density which approximated to that recorded in the field. Plant spacings of 35 mm and 32 mm for low and high density areas respectively at site I2003, and 32 mm for site R2004 were used. This resulted in simulated densities at site I2003 of 129.0 plants m^{-2} and 141.1 plants m^{-2} for the low and high density areas respectively, compared to observed mean values of 129.1 plants m^{-2}

and 141.5 plants m^{-2}. Simulated values at site R2004 were 114.8 plants m^{-2} compared to an observed mean density of 114.3 plants m^{-2}.

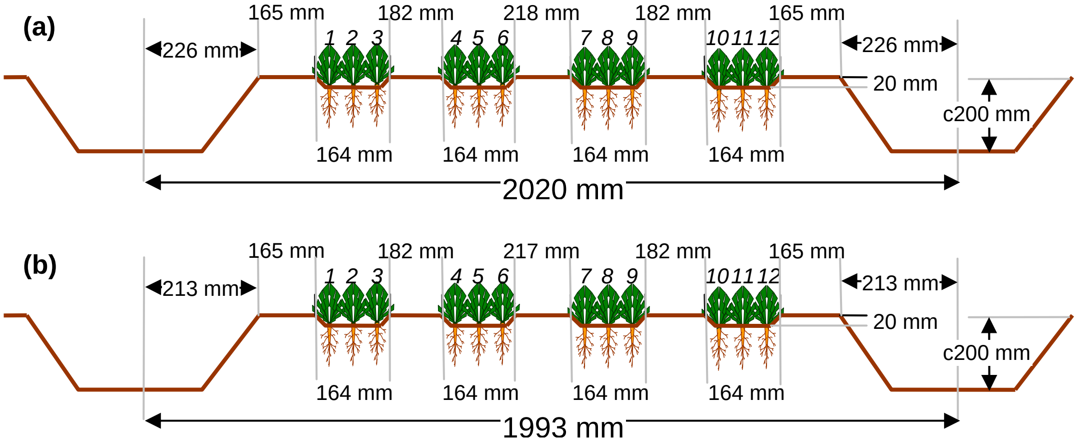


***Figure 5.11** Carrot planting arrangement at site I2003 (a) and site R2004 (b).*

Soil characteristics

Soil chemistry was not measured at either site with the exception of pH, ammonium and total oxides of nitrogen (TON). This was due to the original intention to use the STICS crop model which required less detailed soil chemistry data than the Carrot Calculator model. Therefore it was assumed that the crops were not nutrient limited and the soil nutrient parameters were set to their maximum value (there were no deleterious effects from super-optimal nutrient levels observed within the model). Soil pH values of 7.0 and 7.7 were used for sites I2003 and R2004 respectively. Laboratory bulk density was assumed to be 0.60 g cm^{-3} and 1.05 g cm^{-3} for sites I2003 and R2004 respectively, based on field bulk density measurements and guidance provided in the Carrot Calculator.

Table 5.6 presents the soil physical characteristics used in the Carrot Calculator model. The available water capacity (AWC) for the root-zone was determined from field capacity and permanent wilting point data using the mean depth to which the majority of roots were found (0.44 m and 0.42 m for sites I2003 and R2004 respectively).

Table 5.6 *Soil physical characteristics used to parameterise the Carrot Calculator model.*

Soil Parameter	**Values**	
	I2003	**R2004**
Field bulk density - topsoil only (g cm^{-3})	0.90	1.47
Soil structure score (1-10)	10*	10*
AWC (mm)	81	66
Profile drainage class (0-4)	1*	1*
Soil evaporation constant	7.05*	7.05*
Presence of water table	Absent	Absent

* denotes estimated values

Climate

Meteorological data were obtained from the two local automated meteorological stations and were converted to the file format required for the Carrot Calculator. In order to minimise any potential impact of spatial variability in rainfall on simulations, data for site R2004 was amended for the period 12th May to 11th August using on-farm rain gauge data collected by the grower. No supplemental rainfall data was available outside this period.

Fertiliser

No fertiliser inputs were defined since the soil nutrient values were set to their maximum values (i.e. the crop was not limited by soil nutrient levels).

Irrigation

Irrigation files were created for all plots at both field sites based on measured applications derived from catchcan data (Section 4.3.3). At site I2003 some irrigation events were not recorded; application depths for these dates were therefore assumed to correspond to the scheduled depth.

5.4.2. Carrot Calculator model validation

Using the parameters and inputs described above, carrot crop growth for the relevant plots at both field sites was simulated using the two available calibrated varieties (Red Hot and Chantenay Red Core). A correlation between the simulated root dry biomass and the observed data using linear regression was performed using GenStat® v8.1. The percentage variations in yield accounted for by the model (R^2) and root mean square errors (RMSE) were used to assess model performance. Note that two data-sets were used for this regression: root dry biomass collected through the season (in order to give some data points through the whole spectrum of crop growth); and final yield data converted from fresh weight to dry biomass using the mean root water content (in order to provide some data points with less in-treatment variability than found in the seasonal root dry biomass data). Although the use of both data-sets resulted in a regression which was biased towards the final yield values, this process was considered valid due to the importance of the final yield for this research.

The Carrot Calculator model validation results are presented in Figure 5.12 and Table 5.7. The high R^2 values of 76% to 94% indicated that model fit to the observed data was very good for both sites. However, model fit was better for site R2004 than site I2003, perhaps due to reduced variability in observed data. The Red Hot variety calibration performed marginally better for site I2003 data, but was very similar to Chantenay Red Core for site R2004. Although the Red Hot calibration slightly over-estimated early root yields at site R2004, it appeared to account slightly better for the impact of droughting on the crop. It was therefore concluded that the Red Hot calibration provided the best simulation of carrot crop growth and response to droughting for the two field study areas.

Despite accounting for much of the variability in observed yield, the model suffered from a systematic bias, slightly under-estimating yield for site I2003 and over-estimating yield at site R2004. Therefore, a correction factor derived from the regression equations was applied to the model outputs for the variety Red Hot for both sites I2003 and R2004 (Figure 5.13). Using this modification, RMSE increased slightly for the 2003 site to 2.65 t ha^{-1}, but was reduced for the 2004 site to 1.27 t ha^{-1}. Simulations using the Carrot Calculator model with these correction factors therefore provided a good representation of yield response to varying drought conditions for these two examples. It was therefore concluded that the Carrot Calculator could be used to simulate carrot crop yields for typical production systems in the UK.

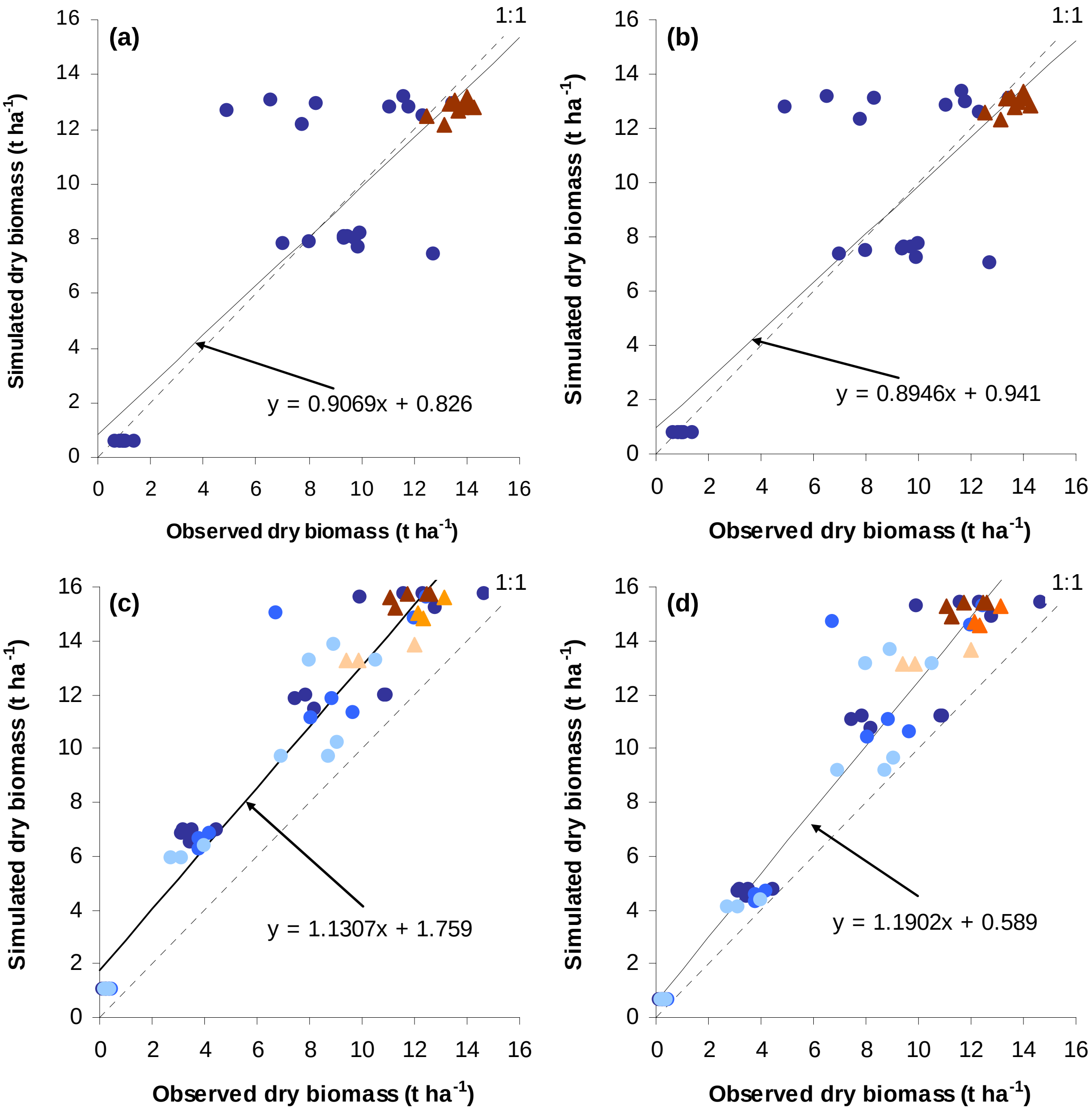


Figure 5.12 Simulated versus observed root dry biomass and linear regressions at: site I2003 using Red Hot calibration (a), site I2003 using Chantenay Red Core calibration (b), site R2004 using Red Hot calibration (c) and site R2004 using Chantenay Red Core calibration (d). Dark blue circles represent root dry biomass observations through the season for FI plots, medium blue SI plots and light blue NI plots. Dark orange triangles represent final yield dry biomass observations for FI plots, medium orange SI plots and light orange NI plots.

Table 5.7 *Derived fit of root dry biomass simulated using the Carrot Calculator model to observed data from sites I2003 and R2004 using both available calibrated varieties.*

Variety and field site		**Regression:** ***simulated*** **= slope x** ***observed*** **+ intercept**			**RMSE (t ha^{-1})**
		Slope ± standard error	**Intercept** ± standard error	**R^2**	
I2003	**Red Hot**	0.9069 ± 0.0821	0.826 ± 0.802	77.6%	2.40
	Chantenay Red Core	0.8946 ± 0.0855	0.941 ± 0.835	75.6%	2.50
R2004	**Red Hot**	1.1307 ± 0.0423	1.759 ± 0.355	93.0%	1.43
	Chantenay Red Core	1.1902 ± 0.0424	0.589 ± 0.356	93.6%	1.44

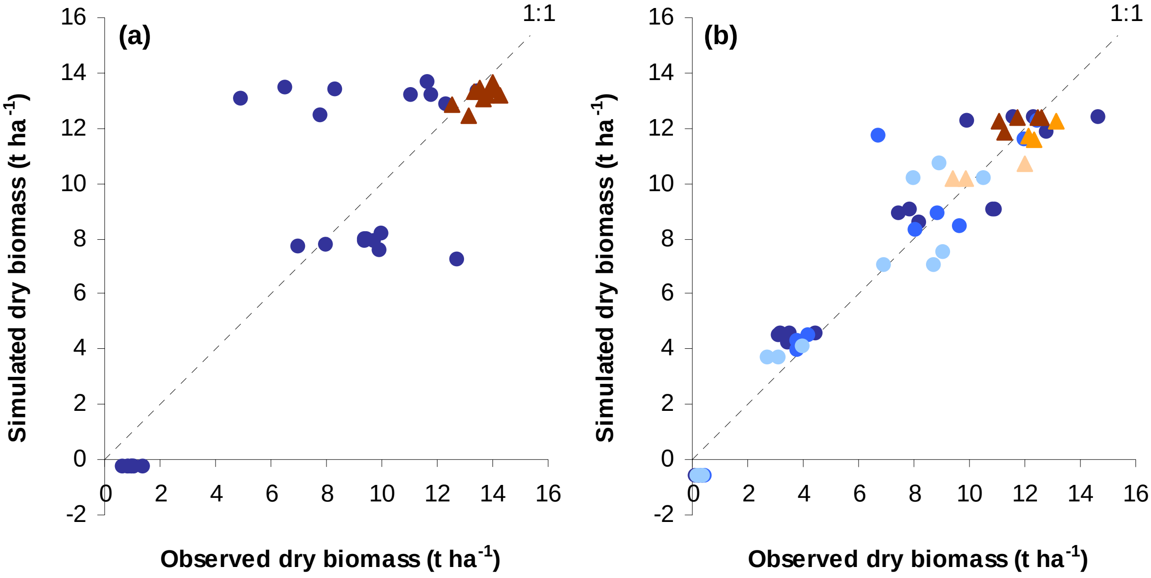


Figure 5.13 *Model outputs for site I2003 (a) and site R2004 (b) using Red Hot calibration and correction factors derived from linear regression equations. Closed circles represent root dry biomass observations through the season, open triangles represent final yield dry biomass observations. Dark blue circles represent root dry biomass observations through the season for FI plots, medium blue SI plots and light blue NI plots. Dark orange triangles represent final yield dry biomass observations for FI plots, medium orange SI plots and light orange NI plots.*

5.5. Summary

A review of potential carrot crop yield simulation models for use in this research originally identified the generic crop model STICS (Brisson *et al.*, 1998; 2002; 2003). However, considerable difficulties in operating and modifying the STICS model to suit the proposed research framework led to its subsequent rejection in favour of the more recent and more suitable Carrot Calculator model (Reid, 2005a,b).

The Carrot Calculator is a relatively simple mechanistic carrot growth model with an accessible Windows™ based graphical user interface and limited data requirements. Its three main components (potential yield, soil water balance and potential yield limiting models) have been validated separately. The model has been used within the New Zealand carrot industry for improving management practices (including irrigation).

Since the Carrot Calculator has been calibrated for two varieties which differ from the Nantes type carrot typically grown in the UK, it was necessary to further validate the model for use in this research. Field work was carried out in 2003 and 2004 to obtain data for model testing. Although rainfall limited the effect of droughting experiments carried out in 2004, findings from these field data were consistent with previous research in demonstrating the deleterious effect of water shortages on carrot production.

Simulations using the Carrot Calculator model assuming a non-limiting nutrient supply demonstrated a good correlation with the observed field data at both field sites. Although there were only marginal differences between simulations using the two calibrated varieties, it was concluded that Red Hot provided the better fit to the observed data. After applying a correction factor derived from linear regression analysis, the Carrot Calculator calibrated with the Red Hot variety provided a good representation of crop yield response to a range of droughted conditions.

It was therefore concluded that the Carrot Calculator model provides an effective tool to evaluate the impact of heterogeneous irrigation applications on carrot crop yield. However, the model does not simulate the impacts of non-uniform irrigation on carrot quality, an increasingly important component of crop production. The development of a carrot quality model to complement the Carrot Calculator is therefore presented in the following chapter.

6. Crop growth simulation II: Crop quality model

This chapter describes the development and validation of a model to predict the effect of non-uniform irrigation on carrot root quality. This model complements the crop yield model (the Carrot Calculator). A rationale for the model development and its principal assumptions are first presented, followed by details of model operation. The validation of the carrot quality model using data collected from the two field sites is then summarised.

6.1. Rationale

The Carrot Calculator model (Reid, 2005a,b) can be used to predict total crop yield as a result of non-uniform irrigation applications. However, it does not provide an estimate of the potential impacts that heterogeneous irrigation applications may have on root quality, which is an increasingly important component of carrot production. Therefore, a model capable of simulating these effects was required.

The model requirements and a review of existing carrot quality related research are presented below.

6.1.1. Model requirements

The requirements of the carrot crop quality simulation model are summarised below:

i) The ability to simulate carrot quality response to spatially and temporally variable soil moisture as a result of irrigation non-uniformity through the growing season;

ii) The facility to handle large datasets in order to estimate spatial variations in carrot crop quality at a field scale, and;

iii) The ability to be linked to the crop yield model (the Carrot Calculator).

6.1.2. Existing carrot quality research

A review of existing research revealed that few studies have attempted to quantify the effect of spatially and temporally variable irrigation on carrot root quality. Indeed crop quality modelling appears to have been largely overlooked for almost all crops

(Chrisosto and Mitchell, 2002). In the UK, Morris *et al.* (1997) carried out a cost-benefit analysis (including both yield and quality) of irrigation on a variety of crops (including carrots) in East Anglia. Other researchers such as Riley and Dragland (1988), Groves and Bailey (1994), Sorensen *et al.* (1997) and Stiles (2002) have identified carrot yield and quality losses due to droughting at critical growth periods. However, none of this research has specifically led to the development of a model for quantifying carrot quality losses as a result of non-uniform irrigation. This is most likely due to the complexity of issues governing the linkages between soil moisture conditions and key carrot crop quality indicators. For example, there are a number of different quality issues (including uniformity of root size, appearance, flavour, colour, texture, disease and physiological disorders) each of which can respond differently to irrigation during different growth stages. In addition, crop husbandry practices may also affect root quality response to irrigation.

It was therefore necessary to develop a new model for this research which would provide an estimate of carrot quality losses due to irrigation non-uniformity. Due to the complex interaction of these agronomic issues, a relatively simple yet scientifically justifiable model was required. This model would be defined using assumptions regarding typical crop husbandry practices and would be restricted to a limited number of key quality indicators. A review of the model limitations in the context of this research is given in Chapter 8.

The principal assumptions for model operation which relate to crop husbandry practices and the selection of appropriate key carrot root quality indicators are described below.

6.2. Principal model assumptions

Typical crop husbandry practices and key root quality indicators were identified through extensive liaison with agronomists and consultants in the UK carrot industry. These are summarised below.

6.2.1. Crop husbandry practices

The response of carrot quality to irrigation is closely related to a number of crop husbandry practices including carrot type and variety, planting arrangement, cropping season, soil type, and the pesticide and nutrient regime. In this study, it was assumed that the model refers to a typical main crop carrot of variety Nairobi, sown in four triple rows on raised beds with 2 m wheel centres in a loamy sand soil on 1st April for harvest after maturity (147 days after sowing i.e. 21 weeks). The crop is assumed to have optimal nutrient and pesticide management, but may be subject to variations in water input as a result of non-uniform irrigation.

Based on estimates from key industry informants, it is assumed that a reference crop with no water stress will attain a total root yield in the region of 90-140 t ha^{-1} with a marketable yield of 80% of the total yield and a premium root yield of 70% of the marketable yield. Both marketable and premium root yields are defined in Section 3.5.3.

6.2.2. Key carrot quality factors

The quality of carrot roots is influenced by variables such as uniformity of root size, appearance, flavour, colour, texture, disease and physiological disorders (Mazza, 1989; Rubatzky and Yamaguchi, 1997; Kotecha *et al.*, 1998; Rubatzky *et al.*, 1999). Three main indicators of carrot root quality were identified using industry advice. These were: crop establishment and uniformity, scab (*Streptomyces scabies*) and root morphology (size, shape and skin texture) (Will, *pers. comm.* 2005; Hipperson, *pers. comm.* 2005; Wright; *pers. comm.* 2005; Birkenshaw, *pers. comm.* 2005; Rickard, *pers. comm.* 2005).

Disease and physiological disorders other than those noted above can also be important to carrot quality. The effect of irrigation on diseases other than scab and issues such as fanging, flavour and pesticide and nutrient mobilisation are discussed more generally in Section 6.4. However, the effects of non-uniform irrigation on these additional quality-related issues are not considered in the model.

6.3. Model operation

The carrot quality model presented in this chapter was developed using extensive liaison with key informants in the UK carrot industry. The model is based on the theory of yield response to water developed by Doorenbos and Kassam (1986) and uses a similar approach to Morris *et al.* (1997) for estimating the impact of timing of irrigation on crop quality. The model operates in a spreadsheet format (Microsoft® Excel). An overview of the carrot quality model and a detailed description each stage is provided below.

6.3.1. Overview

The model adopts the Doorenbos and Kassam (1986) approach in identifying periods of crop drought stress which may impact on quality through comparison of cumulative actual crop evapotranspiration rates (ET_a) to cumulative potential (unstressed) crop evapotranspiration rates (ET_c). Both ET_a and ET_c values for a simulated carrot crop on a selected day after sowing are obtained from the Carrot Calculator outputs. Reductions in root quality relating to the three key root quality indicators are assumed to be directly proportional to the degree of stress that the crop experiences during each growth stage as defined in Table 6.1 (see also Figure 3.5). From the quality losses which occur during each period, a total quality loss is calculated. This is used to reduce the optimal (i.e. no water stress) marketable proportion of the total root yield for the crop (calculated by the Carrot Calculator) to give the marketable yield in t ha^{-1}. The optimal proportion of marketable roots which fall into the premium root category is similarly reduced by this total quality loss.

Table 6.1 *Defined carrot growth stages for root quality estimation.*

Period (weeks after sowing)	**1-9**	**9-13**	**13-17**	**17-21**	**21-harvest**
Carrot growth stage	Germination and establishment to 2-6 leaves "pencil" stage	Start of root enlargement	Root bulking	Root bulking	Maturity

6.3.2. Determining crop drought stress

Potential crop evapotranspiration (ET_c) and actual crop evapotranspiration (ET_a) are calculated using the Carrot Calculator for each growth stage period. The ET_a of the crop in an unstressed situation will equal ET_c. However in conditions of water shortage, ET_a will be reduced. A stress index (SI) is calculated for each period using Equation 6.1.

$$SI = 1 - ET_a/ET_c \qquad \text{Equation 6.1}$$

where SI = 0 when there is no drought stress on the crop and 1 when drought stress results in zero evapotranspiration. The SI for each period is assumed to directly affect crop quality for each of the key root quality factors.

6.3.3. Defining key root quality indicators

Crop establishment and uniformity (K_{EU})

Of the three key quality indicators, crop establishment and uniformity is the most critical to ensure that target plant densities are reached, leading to the greatest possible uniformity in root size at harvest (Will, *pers. comm.* 2005). To achieve this, sufficient uniformly distributed water must be available early in the season to allow the crop to establish and to prevent uneven inter-plant competition (Salter *et al.*, 1981; Groves and Bailey, 1994; Rubatzky and Yamaguchi, 1997, Lada and Stiles, 2004). If the crop does not establish properly, or if growth is non-uniform, it is effectively impossible to rectify this later in the season. Based on industry advice, the assumed maximum potential quality losses due to poor crop establishment and uniformity caused by complete drought stress for each period (K_{EU}) are shown in Table 6.2. Note that a complete loss in root quality is assumed in the most important period (1-9 weeks after sowing) since total drought conditions here would result in crop failure.

Table 6.2 *Assumed maximum potential quality losses due to poor crop establishment and uniformity caused by complete drought stress during each growth period (K_{EU}).*

Period (weeks after sowing)	**1-9**	**9-13**	**13-17**	**17-21**	**21-harvest**
Maximum potential quality loss for period K_{EU} (fraction)	1.0	0.6	0.3	0.0	0.0

Carrot scab (K_S)

Carrot scab (*Streptomyces scabies*) is considered to be the second most important indicator of root quality (Will, *pers. comm.* 2005). Scab control using irrigation (especially in sandy soils) is important up to the 6 leaf stage, although irrigation is not typically recommended before the 4 leaf stage (Bailey, 1990; Groves and Bailey, 1994; Schoneveld, 1994; Sorensen *et al.*, 1997; Wright, *pers. comm.* 2005). Similarly to crop establishment and uniformity, if a significant scab problem develops early in the season it cannot be rectified later. Based on industry advice, the assumed maximum potential quality losses due to scab caused by complete drought stress for each period (K_S) are shown in Table 6.3. The maximum quality loss of 30% due to scab is assumed during the most important period (1-9 weeks after sowing). Note that it is possible for scab to infect plants which are not drought stressed. However, such conditions are beyond the scope of this model and the assumption is therefore made that no scab infection will occur during periods when there is no drought stress.

Table 6.3 *Assumed maximum potential quality losses due to scab caused by complete drought stress during each growth period (K_S).*

Period (weeks after sowing)	**1-9**	**9-13**	**13-17**	**17-21**	**21-harvest**
Maximum potential quality loss for period K_S (fraction)	0.3	0.1	0.0	0.0	0.0

Root morphology (K_{RM})

Root morphology (i.e. root size, shape and skin finish) is considered to be the third most important indicator of root quality (Will, *pers. comm.* 2005). The critical period for root morphology is during the early to mid-season growth stages. Root size is greatly increased during this bulking period, contributing primarily to yield but also ensuring that roots meet the size requirements of markets (Rubatzky and Yamaguchi, 1997; Rubatzky *et al.*, 1999). The objectives of a grower concerning root size will depend on the intended market. Root shape can become ribbed, twisted or otherwise deformed if water shortage occurs during early to late mid-season (weeks 9-21) (Mazza, 1989; Rubatzky *et al.*, 1999). Skin finish can also be affected by drought stress during this time and through to harvest, developing cracks, splits or a “crinkly” finish (Rubatzky and Yamaguchi, 1997; Rubatzky *et al.*, 1999). Based on industry advice, the assumed maximum potential quality losses due to root morphology issues caused by complete drought stress for each period (K_{RM}) are shown in Table 6.4. Note that a maximum quality loss of 30% due to root morphology issues is assumed during the most important period (9-13 weeks after sowing).

Table 6.4 *Assumed maximum quality losses due to root morphology caused by complete drought stress during each growth period (K_{RM}).*

Period (weeks after sowing)	**1-9**	**9-13**	**13-17**	**17-21**	**21-harvest**
Maximum potential quality loss for period K_{RM} (fraction)	0.1	0.3	0.2	0.1	0.0

Figure 6.1 illustrates the assumed maximum potential quality losses caused by complete drought stress during each growth period relating to the three key quality indicators.

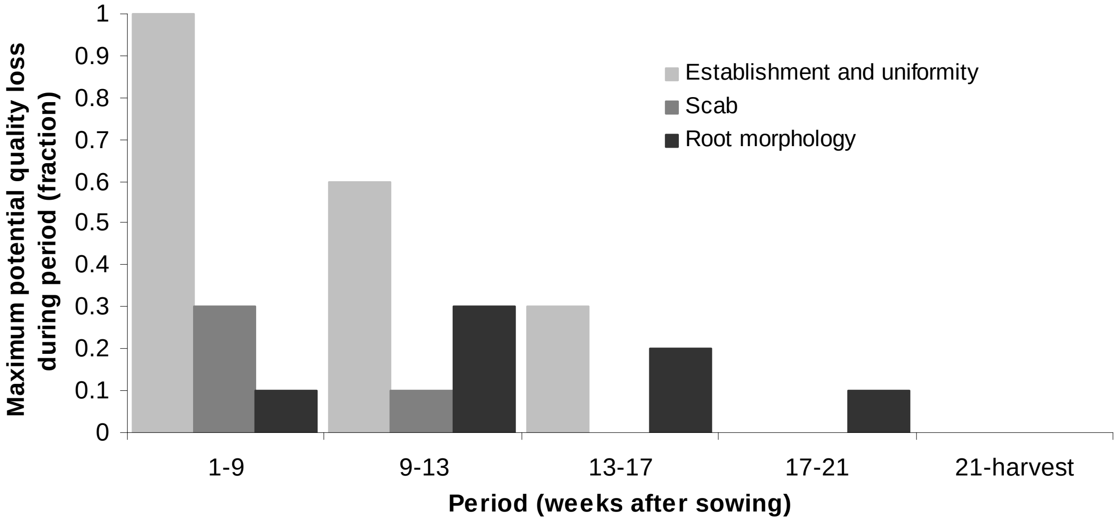


Figure 6.1 *Assumed maximum potential carrot quality losses caused by complete drought stress during each growth period.*

6.3.4. Calculating total quality loss

The quality losses (Q_i) relating to each of the three quality indicators (Q_{EU}, Q_S and Q_{RM}) are assumed to be cumulative through the season and are calculated using Equation 6.2.

$$Q_i = 1- (1 - K_i.SI)_{1\text{-}9}(1 - K_i.SI)_{9\text{-}13}(1 - K_i.SI)_{13\text{-}17}(1 - K_i.SI)_{17\text{-}21}(1 - K_i.SI)_{21\text{-harvest}}$$

Equation 6.2

where SI is the stress index and K_i is the maximum potential quality loss related to the specified quality indicator for the period concerned (K_{EU}, K_S or K_{RM}).

For example, if there was a 15% loss due to scab during weeks 1-9 after sowing, then there will be only 85% which may be affected by further quality loss. An additional 5% quality loss from this 85% due to scab in weeks 9-13 would therefore result in only 80.75% which may be affected by further quality loss.

The total quality loss fraction (Q_t) is calculated similarly by multiplying the fractions of quality remaining after Q_i losses using Equation 6.3.

$$Q_t = 1-(1-Q_{EU})(1-Q_S)(1-Q_{RM})$$

Equation 6.3

where Q_{EU}, Q_S and Q_{RM} are the Q_i values calculated using Equation 6.2 for each of the quality indicators.

Caution needs to be exercised in using the individual Q_i values to describe the absolute quality loss relating to any specified quality indicator, since the overall quality loss depends on the product rather the sum of the losses relating to each quality indicator. Hence, for clarity, it is assumed that losses relating to poor crop uniformity occur first, losses relating to scab occur second and losses relating to root morphology issues occur last. Equations 6.4-6.6 describe the calculation of the absolute losses ($Q_{i\text{absolute}}$) relating to each quality indicator.

$$Q_{EUabsolute} = Q_{EU}$$

Equation 6.4

$$Q_{Sabsolute} = (1-Q_{EU})-(1-Q_{EU})(1-Q_S)$$

Equation 6.5

$$Q_{RMabsolute} = (1-Q_{EU})(1-Q_S)-(1-Q_{EU})(1-Q_S)(1-Q_{RM})$$

Equation 6.6

6.3.5. Calculating marketable and premium root yields

The marketable percentage of roots ($Y_{M\%}$) can be calculated from the total quality loss (Q_t) using Equation 6.7.

$$Y_{M\%} = Y_{Mmax\%}(1-Q_t)$$

Equation 6.7

where $Y_{Mmax\%}$ is the potential marketable percentage in a typical crop which experienced no water shortages (assumed to be 80%).

The marketable yield (Y_M, in t ha^{-1}) is then calculated using Equation 6.8.

$$Y_M = Y_t Y_{M\%}$$

Equation 6.8

where Y_t is the total fresh root yield (t ha^{-1}) as calculated by the Carrot Calculator model assuming a root water content of 88%.

Similarly, the premium root percentage ($Y_{P\%}$) is calculated using Equation 6.9.

$$Y_{P\%} = Y_{Pmax\%}(1-Q_t)$$

Equation 6.9

where $Y_{Pmax\%}$ is the potential percentage of marketable roots which fall in the premium category in a typical crop which experienced no water shortages (assumed to be 70%).

Premium root yield (Y_P, in t ha^{-1}) is then calculated using Equation 6.10.

$$Y_P = Y_M Y_{P\%}$$

Equation 6.10

6.4. Effect of irrigation on other quality issues

6.4.1. Diseases and pesticide action

Many carrot foliar and root diseases may be encouraged by irrigation which can help to provide the moist, humid conditions that are favourable for infection. Additionally, over-irrigation early in the season can lead to increased canopy cover which can also help to provide favourable conditions for diseases (Nonnecke, 1989). Economically important diseases which may be encouraged by extended periods of wet foliage and/or soil include: leaf blight (*Alternaria dauci*), black rot (*Alternaria radicina*), sclerotinia (*Sclerotinia sclerotiorum*), cavity spot (*Pythium violae* and *P. sulcatum*), bacterial soft rots (*Erwinia carotovora* and *Pseudomonas* spp.) and liquorice root rot (*Mycocentrospora acerina*) (Persley, 1994; Rubatzky *et al.*, 1999; Thomas and Martin, 2002; Pettitt and Gladders, 2003; HDC, 2005).

Irrigation (in particular over-irrigation) can also affect the activity of residual pesticides. Residual nematicides applied to control root fanging can be leached from the soil by excessive irrigation and/or rainfall (White, 2004; Will, *pers. comm.* 2005). Pre-emergence herbicides may also be leached by excessive irrigation/rainfall and can actively cause root fanging by damaging the tap root apex (Will, *pers. comm.* 2005).

6.4.2. Physiological disorders

Irrigation (in particular over-irrigation) may also be detrimental to carrot root quality in other ways. For example, meristematic cells at the tap root apex can become damaged after only a few hours of waterlogging, leading to reduced root growth and increased incidence of fanging (White and Strandberg, 1979; Nonnecke, 1989; Saiful Islam, 1998). Over-watering has also been found to cause an increase in cork-like growths and fine hair-like roots on the tap root (Bradley *et al.*, 1967; Rubatzky *et al.*, 1999). Some researchers have found an increase in split roots under high intensity irrigation regimes, particularly when large amounts of water were applied after a period of drought (Riley, 1989; Batra and Kalloo, 1990b; Benjamin *et al.*, 1997; Rubatzky *et al.*, 1999).

Fluctuating soil water conditions may also affect root smoothness (Rubatzky *et al.*, 1999) and can lead to the development of bulbous roots (Will, *pers. comm.* 2005; Wright, *pers. comm.* 2005). In addition, carrot flavour and beta-carotene content has been found to be decreased as a result of heavy irrigation (Bradley *et al.*, 1967; Nortje and Henrico, 1986; Bailey, 1990). However, Rolbiecki *et al.* (2000) demonstrated that irrigation was beneficial in improving carrot quality by reducing root nitrate contents.

6.4.3. Summary

Although the majority of the disease and physiological disorders highlighted above appear to demonstrate a negative effect of irrigation on carrot quality, it should be noted that nearly all the detrimental effects typically occur due to over- or untimely irrigation. Provided that irrigation is carefully managed, it can provide considerable benefits to carrot quality. In addition, it is important to note that disease outbreaks and physiological disorders may result from a combination of factors other than solely water inputs. These include climate, cultivar, previous crop rotations, soil type and the disease infection risks of the soil and surrounding area.

It is difficult to model the effect of irrigation on these other carrot quality-related issues since both the Carrot Calculator and the root quality model only show a deleterious effect on crop yield and quality as a result of water shortages. Neither model allows for reductions in yield and quality as a result of excess water. However, on the sandy, free-draining soil used in this study, these effects are assumed to be minimal.

6.5. Validation of the carrot quality model

The agronomic conditions assumed in the carrot quality model were similar to those observed at site R2004. The model performance was therefore tested against the observed marketable and premium root yields for the eleven experimental irrigation plots at that site. The failure of the experimental irrigation plots at site I2003 combined with differences in crop variety, husbandry practices and soil characteristics precluded the use of data from this site for testing the carrot quality model.

For this validation, the Carrot Calculator was parameterised and operated as described in Section 5.4.1. The Carrot Calculator was used to generate crop yield, ET_c and ET_a

outputs for each of the eleven experimental plots at site R2004. These outputs were generated for dates corresponding to the relevant critical periods of crop growth required for the carrot quality model. The spreadsheet-based carrot quality model was then used to estimate quality losses due to poor establishment and uniformity, scab and root morphology issues. From these estimated quality losses, marketable and premium root yields for the experimental plots were then derived.

Table 6.5 presents the quality losses estimated for site R2004. The carrot quality model suggested that there was no quality loss in the fully irrigated (FI) plots, with the exception of plots 5 and 10 (both of which received sub-optimal irrigation applications during part of the season). The simulated semi-irrigated (SI) plots showed a quality loss of between 1% and 8%. However, the simulated non-irrigated (NI) plots showed a quality loss of 21% (except plot 24, which received some irrigation during the first event). This corresponded to an average simulated marketable yield of around 79%, 77% and 66% and an average simulated premium root yield of around 69%, 67% and 58% for the FI, SI and NI plots respectively. Most of the quality losses were attributed to poor crop establishment and uniformity and root morphology issues.

Table 6.5 *Estimated crop quality losses (fractions) from the optimum marketable and premium root percentage ($Y_{Mmax\%}$ and $Y_{Pmax\%}$) relating to crop establishment and uniformity, scab, root morphology and total quality loss for experimental irrigation plots at site R2004.*

Indicator of quality loss	**Fully irrigated plots:**					**Semi-irrigated plots:**			**Non-irrigated plots:**		
	2	**5**	**7**	**10**	**17**	**16**	**18**	**22**	**3**	**12**	**24**
Establishment and uniformity ($Q_{EUabsolute}$)	0.00	0.02	0.00	0.00	0.00	0.02	0.05	0.00	0.12	0.12	0.05
Scab ($Q_{Sabsolute}$)	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00
Root morphology ($Q_{RMabsolute}$)	0.00	0.01	0.00	0.00	0.00	0.02	0.02	0.00	0.08	0.08	0.05
Total root quality loss (Q_t)	**0.00**	**0.04**	**0.00**	**0.01**	**0.00**	**0.03**	**0.08**	**0.01**	**0.21**	**0.21**	**0.10**

Comparison of these simulated results to the observed graded root yields (Table 5.5) suggested that the carrot quality model performed relatively poorly in simulating quality losses relating to the three quality indicators (particularly scab). For example, the observed scab levels in some fully irrigated plots were as high as 3.7% (plot 2) and up to 9.1% in the semi-irrigated plot 16, whereas both non-irrigated plots 3 and 12 showed no signs of scab infection. In addition, there was a large degree of variability in root quality between observed plots with similar irrigation regimes. This is likely to reflect the complexity of the issues surrounding crop quality, with spatially variable factors such as disease susceptibility, soil physical characteristics and soil fertility playing an important role in influencing root quality.

The predicted marketable and premium root yields were plotted against observed final yield data for site R2004 (Figure 6.2). A linear regression analysis was performed using GenStat® v8.1 from which R^2 and RMSE values were derived and used to evaluate model performance (Table 6.6). In general, model performance was moderate for marketable root yield simulation, but poorer for premium root yield simulation. The comparatively small proportion of the observed data which was accounted for by the model (34% and 6% for marketable and premium yields respectively) was largely due to the variability within the observed data. The RMSE values were comparatively high, again reflecting the variability in observed data. Despite this large degree of variability, the data were largely clustered near to a 1:1 relationship, with FI plots tending to display higher marketable and premium root yields than SI or NI plots.

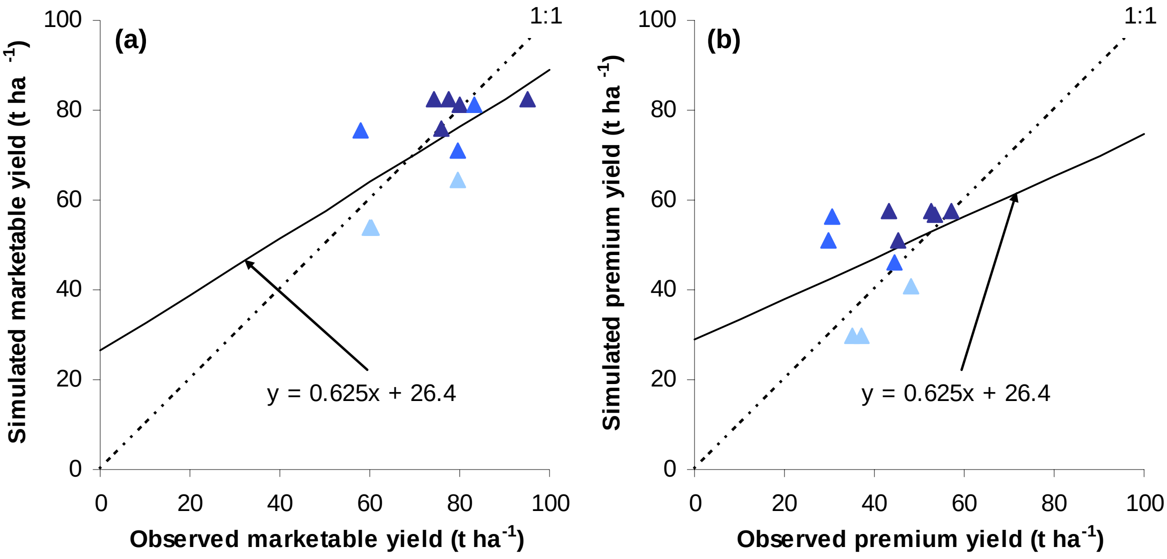


***Figure 6.2** Simulated versus observed carrot yield results from carrot quality model for marketable yield (a) and premium root yield (b) for site R2004. Dark blue colouring indicates FI plots, medium blue SI plots and light blue NI plots.*

Table 6.6 *Carrot quality model validation results for site R2004.*

Model performance for:	Regression: *simulated* = slope x *observed* + intercept Slope ± standard error.	 Intercept ± standard error	 R^2	RMSE $(t\ ha^{-1})$
Marketable yield $(t\ ha^{-1})$	0.625 ± 0.253	26.4 ± 19.2	33.8%	9.0
Premium root yield $(t\ ha^{-1})$	0.456 ± 0.353	28.9 ± 15.6	6.2%	10.4

It was therefore concluded that, although the carrot quality model was not capable of accurately determining quality losses relating to specific quality indicators (particularly scab) at site R2004, it performed adequately in simulating overall marketable root yield differences as a result of the differing irrigation regimes at the site. However, it did not simulate premium root yields as well. Nevertheless, the model represents the first attempt to estimate carrot quality as a result of crop water inputs and will therefore provide valuable information in this research.

The carrot quality model and its outputs and validation were presented to key informants within the UK carrot industry. There was a general consensus that, despite the limitations of the model, it provided an acceptable method for estimating marketable and premium root yields for carrots grown under typical agronomic conditions.

6.6. Summary

A simple spreadsheet-based model to estimate carrot root quality as a result non-uniform irrigation through the season has been developed. The model works on the principle that plant stress caused by drought affects crop quality in different ways at different crop growth stages. Marketable and premium root yields are reduced from an optimal percentage of the total yield by a quality loss factor which is calculated from the degree of stress that the crop experiences during critical growth stages. Three key indicators of root quality are considered – crop establishment and uniformity, scab and root morphology. Other disease and physiological issues, particularly those relating to excessive water input were not modelled.

The carrot quality model was tested against crop quality data collected from field site R2004. Although the carrot quality model did not perform well in determining quality losses relating to specific quality indicators (particularly scab) when compared to observed data, it performed adequately in simulating marketable root yield differences as a result of the differing irrigation regimes at the site. However, it did not predict premium root yields as well. Nevertheless, the model represents the first attempt to estimate carrot quality as a result of crop water inputs and will therefore provide valuable information in this research., It was therefore concluded, with industry support, that the new carrot quality model developed in this chapter provides a simple but useful estimation of the potential impacts of non-uniform irrigation on carrot quality under typical (but limited) cultivation conditions.

The crop growth simulation component of the integrated modelling approach therefore combines a crop yield model (the Carrot Calculator) and a crop quality model. The application of these combined models is presented in the following chapter.

7. Integrated modelling: Simulating the impact of equipment and management strategies on irrigation uniformity and crop production

This chapter describes how an integrated modelling approach has been developed and used to simulate the impact of raingun equipment and management strategies on irrigation uniformity and crop production. Firstly, a brief summary of the integrated approach that combines a raingun simulation model with crop growth simulation models is given. A range of equipment and management scenarios for simulation and evaluation are then outlined. The parameterisation of the raingun and crop growth models is then described. Finally, the outputs from the scenario modelling and two examples showing further potential uses of the integrated approach are presented.

7.1. The integrated modelling approach

The integrated modelling approach outlined in Figure 2.1 can effectively be described as a two stage process:

i) The spatial heterogeneity in irrigation application at the field level is simulated using the TRAVGUN-TRAVELLER model for a range of equipment and management strategies;

ii) Selected model outputs from the TRAVGUN-TRAVELLER model are then used as inputs to the Carrot Calculator and crop quality models to assess the impacts of non-uniform irrigation on carrot crop yield and quality.

In this research, the raingun simulation model and the crop growth models have been linked using a data-bridge approach. This provides a simple and robust method for exchanging data between existing models without the need for developing a separate user interface. It also avoids the problems associated with embedding the routines and code from separate models written in differing programming languages within a single program. Furthermore, a data-bridge approach also provides a great deal of flexibility by allowing the subsequent updating of models (e.g. new releases) without impacting on the integrated modelling framework.

This integrated approach therefore allows detailed evaluation of the implications of changing raingun equipment and management strategies for crop production. The approach could also be used to evaluate other irrigation water related issues, for example assessing the impacts of climate change on irrigated crop production.

It should be noted that all data relating to irrigation uniformity and crop production are derived from a calculation area between the travel lanes of the first and last pull, discounting the top and bottom 50 m of the field to exclude edge effects (Figure 4.1).

7.2. Equipment and management scenarios for simulation

The combined effect of various raingun equipment settings with particular management strategies can have a profound impact on irrigation application uniformity as described in Section 3.2. In order to improve irrigation uniformity, a practical strategy would therefore need to take into account the following variables: field orientation, lane spacing, trajectory angle, sector angle and time of irrigation (day versus night).

The TRAVGUN-TRAVELLER raingun model can be used to simulate the impact of these variables on application uniformity. However, to assess the impact of changing the trajectory angle would have required calibration of TRAVGUN for a range of rainguns operating at different trajectory angles. This was not possible within the scope of this research. Therefore, only strategies involving changes to field orientation, lane spacing, sector angle and time of irrigation (day versus night) were evaluated. Justification of the range of values chosen for each of these variables is presented below.

7.2.1. Field orientation

Field orientation relative to the prevailing wind during irrigation can be an important factor in application uniformity. This is because periods during an irrigation when the prevailing wind blows parallel to the raingun travel direction can systematically reduce application uniformity. In this research, it is assumed that the field orientation refers to the direction of the travel lanes as seen from the hose-reel (i.e. the raingun travel direction minus 180°).

In the majority of situations, field topography dictates the orientation of travel lanes. Field orientation cannot usually be altered during a season in response to wind conditions and, once established, it is unlikely to be changed from season to season. However, opportunities do exist where there is a choice of orientation – e.g. in large, broadly square fields with a water source in one corner, or during planning stages in which new fields are being incorporated into the irrigation command. Therefore it was necessary to examine the extent to which field orientation relative to the prevailing wind may have on raingun irrigation uniformity.

The TRAVGUN-TRAVELLER model can simulate irrigation application for a field orientated in any direction. Since there is symmetry about the raingun travel axis, it was necessary only to consider field orientations relative to the prevailing wind through a 180° arc. Therefore, the impacts of field orientations of 0°, 45°, 90° and 135° to the prevailing wind were selected for investigation.

7.2.2. Lane spacing

The UK industry recommended lane spacing is 72 m for a typical hose-reel raingun used in field scale horticulture. However alternative spacings may be more appropriate under differing wind conditions and/or equipment settings. Although there are limitations to changing lane spacing in response to current or forecast wind conditions (e.g. as a result of field shape, water source location, labour or equipment constraints), this remains a viable option for reducing raingun irrigation non-uniformity in certain situations.

In this research, four alternative lane spacings were investigated, namely 50 m, 60 m, 70 m and 80 m. These were chosen to represent practical alternatives to the industry standard spacing, and were based on multiples of 5 m to correspond with the requirements of the TRAVGUN-TRAVELLER model.

7.2.3. Sector angle

Changing the sector angle for raingun rotation affects the application pattern and rate with consequences for application uniformity under different wind conditions. The majority of previous studies have indicated that a sector angle of between 180° and 240° tended to provide the best uniformity at low wind speeds but sector angles of 240° to 270° provided better uniformity at higher wind speeds. In the UK, although most raingun sector angles broadly conform to this range of values, there is known to be little operator understanding of the impact that sector angle may have on application uniformity.

Irrigation applications using any defined sector angle can be simulated using the TRAVGUN-TRAVELLER model. The sector angles to be evaluated in this study were selected from the range identified by previous work, namely 180°, 210°, 240° and 270°.

7.2.4. Day versus night irrigation

Wind speeds generally show considerable diurnal variation, typically being half as strong at night compared to during the day. Consequently, growers are often advised to irrigate at night to reduce the impact of wind distortion on application uniformity and also to limit evaporative losses. There are some practical restrictions on the extent to which growers can irrigate at night – these primarily relate to labour or equipment constraints, health and safety issues and the ability to monitor performance during irrigation. Many growers already irrigate at night in order to complete irrigation schedules and to maximise raingun use, particularly during peak demand periods. However, reducing application non-uniformity does not appear to be the main driver for irrigating at night. Therefore, the impact of night-time irrigation on irrigation uniformity warrants further investigation.

The TRAVGUN-TRAVELLER model can simulate irrigation application for raingun pulls starting at any time (at 15 minute intervals). To reflect typical practices, a start time of 07:00 hours was assumed for day time irrigation and 19:00 hours for night time irrigation.

7.2.5. Permutations of factors affecting application uniformity

In summary, four different field orientations relative to the prevailing wind (0°, 45°, 90° and 135°), four lane spacings (50 m, 60 m, 70 m and 80 m), four sector angles (180°, 210°, 240° and 270°) and two irrigation timings (day and night) were selected for scenario modelling. The impacts of each permutation of these variables on the spatial heterogeneity of irrigation application were simulated using the TRAVGUN-TRAVELLER model (total number of scenarios = 128).

7.3. Parameterisation of the integrated model components

Irrigation in the UK is supplemental to rainfall. In order to incorporate the effects of seasonal climatic changes, it was therefore necessary to derive long-term daily climatic datasets for use in both the raingun and crop growth models. In addition, it was also necessary to appropriately parameterise the model components to reflect typical carrot production under the selected irrigation strategies. A summary of the climate data used for simulation, the process used to schedule irrigations during each season of climate data and the parameterisation of the models is given below.

7.3.1. Climate data and irrigation scheduling for integrated modelling

The TRAVGUN-TRAVELLER model requires wind speed (m s^{-1}) and wind direction (°) data at 15 minute intervals. The Carrot Calculator and carrot quality models require daily minimum and maximum temperature (°C), global radiation (MJ m^{-2}) and rainfall (mm) for each cropping season. A number of years of climate data were therefore processed for use in order to reflect typical in-field climatic conditions for raingun irrigation and crop growth. These data were obtained from meteorological stations located near field sites I2003 and I2004. Climate data for site I2003 was obtained for the period 1998-2004 (denoted I1998-I2004 for clarity). Climate data for site R2004 was obtained for the period 1999-2004 (denoted R1999-R2004 for clarity). This gave a total of 13 years of climate data for use in the modelling processes.

For each year, it was necessary to determine the theoretical timing and depth of irrigation which would be applied during the growing season based on typical industry practices. This required the definition of a set of assumptions regarding typical carrot crop husbandry (Table 7.1).

Table 7.1 *Crop husbandry assumptions used for scheduling irrigation events.*

Crop growth or husbandry parameter	Model values
Crop variety	Maincrop carrots (variety Nairobi)
Sowing date	1st April
Harvest date	1st October (183 days after sowing, DAS)
Pesticide and nutrient regime	Optimal (only water availability limits crop growth)
Soil type	Loamy sand
Location	East Anglia, UK

The timing and depth of irrigation applications in each year were simulated using a soil water balance model termed "WaSim" (Counsell and Hess, 2000). The crop characteristics required for model parameterisation were derived from observations of crop growth at site R2004 and from literature, where necessary. The soil characteristics were assumed to correspond to the default values for loamy sand provided in the WaSim model. The set of assumptions used to parameterise the WaSim soil water balance model are defined in Table 7.2.

Table 7.2 *Assumed crop and soil values used for WaSim model parameterisation.*

Crop growth parameters for carrot variety Nairobi	**Assumed value**
Emergence date	21 DAS (21st April)
Date of 20% cover	74 DAS (13th June)
Date of full cover and maximum rooting depth	109 DAS (18th July)
Date of maturity and harvest	183 DAS (1st October)
Maximum cover	100%
Crop coefficient at maximum cover	1.05*
Planting depth	0.01 m
Maximum root depth	0.4 m
Soil parameters for loamy sand	**Assumed value****
Water content at saturation	43.7%
Water content at field capacity	16.8%
Water content at permanent wilting point	5.5%
Hydraulic conductivity	2.0 m d^{-1}
Water content at sowing date	16.8% (field capacity)

* Allen *et al*., (1998)
** All soil parameters for loamy sand based on WaSim default values (Counsell and Hess, 2000)

WaSim also requires an irrigation schedule to be defined. Irrigation events were triggered at specific soil moisture deficits according to a defined irrigation schedule, based on literature and modified according to industry advice (Table 7.3).

Table 7.3 *Typical irrigation schedule for maincrop carrots grown on a loamy sand soil.*

Crop growth period	**Irrigation application (mm)**	**Trigger soil moisture deficit (mm)**
Sowing to 4 leaf stage (56 DAS)	No irrigation	No irrigation
4 leaf stage (57 DAS) to start of root bulking (91 DAS)	15	15
Start of root bulking (92 DAS) to 140 DAS	25	30
140 DAS to harvest on 1st October (183 DAS)	25	35

Using the above parameters, the seasonal crop water use and soil moisture deficits were simulated for each year of climate data using the WaSim model. Table 7.4 summarises the climatic conditions during the growing season and the theoretical seasonal irrigation depths for each year simulated. There was a relatively large variation in total ET_o and rainfall during the growing season between different years – with ET_o and rainfall ranging from 344-496 mm and 193-602 mm respectively. Consequently, the theoretical seasonal irrigation requirements also varied considerably. For example, years with a relatively high irrigation need (e.g. I1998, I2002 and I2003) required between 7 and 11 irrigation events to fulfil crop water requirements, totalling between 165 and 235 mm of applied water. Conversely, years with a low irrigation need (e.g. R1999, R2000 and R2001) required only 2-3 irrigation events, totalling between 40 and 65 mm.

Table 7.4 *Summary of the ET_o and rainfall during the growing season (1^{st} April to 1^{st} October) for all climate data showing irrigations scheduled using WaSim.*

Climate data series	Total ET_o (mm)	Total rain (mm)	Total seasonal deficit (mm)	No. of irrigations	Seasonal depth of irrigation applied (mm)
I1998	446	381	65	7	165
I1999	453	405	47	5	115
I2000	368	365	3	5	115
I2001	411	403	8	4	80
I2002	430	195	235	9	185
I2003	496	193	303	11	235
I2004	452	602	-150	4	60
R1999	449	384	65	6	140
R2000	357	439	-82	3	65
R2001	344	457	-113	2	40
R2002	396	323	73	3	65
R2003	431	291	140	4	100
R2004	402	354	48	5	95

Figure 7.1 summarises the wind conditions during each of the 68 scheduled irrigations above, both for day time and night time irrigation simulation options. Mean wind speeds were typically between 1 m s^{-1} and 2.5 m s^{1} during daytime irrigations but were only about half as strong at night. However, wind speeds varied considerably more during night irrigations than during the day. Indeed, the strongest mean wind speed during an irrigation event (3.3 m s^{-1}) was recorded at night, with gusts of up to 8.1 m s^{-1}. Winds were recorded from most directions, but were predominantly between south west and north west, with a relatively large number from the east (particularly at night).

Wind speeds during the scheduled irrigation events did not often reach the upper limit of 4-5 m s^{-1} beyond which raingun irrigation is generally not advised (e.g. Schull and Dylla, 1976a,b; Growcom, 2004b). However, considerable distortion of the wetted pattern from a raingun (and consequently low uniformity) can result from relatively low wind speeds of <3 m s^{-1} (e.g. Schull and Dylla, 1976a,b; Oakes and Rochester, 1981; Musa, 1988; Al-Naeem, 1993). It was therefore assumed that the range of wind values presented in Figure 7.1 were typical of the likely wind conditions under which irrigation non-uniformity may occur in this area of the UK.

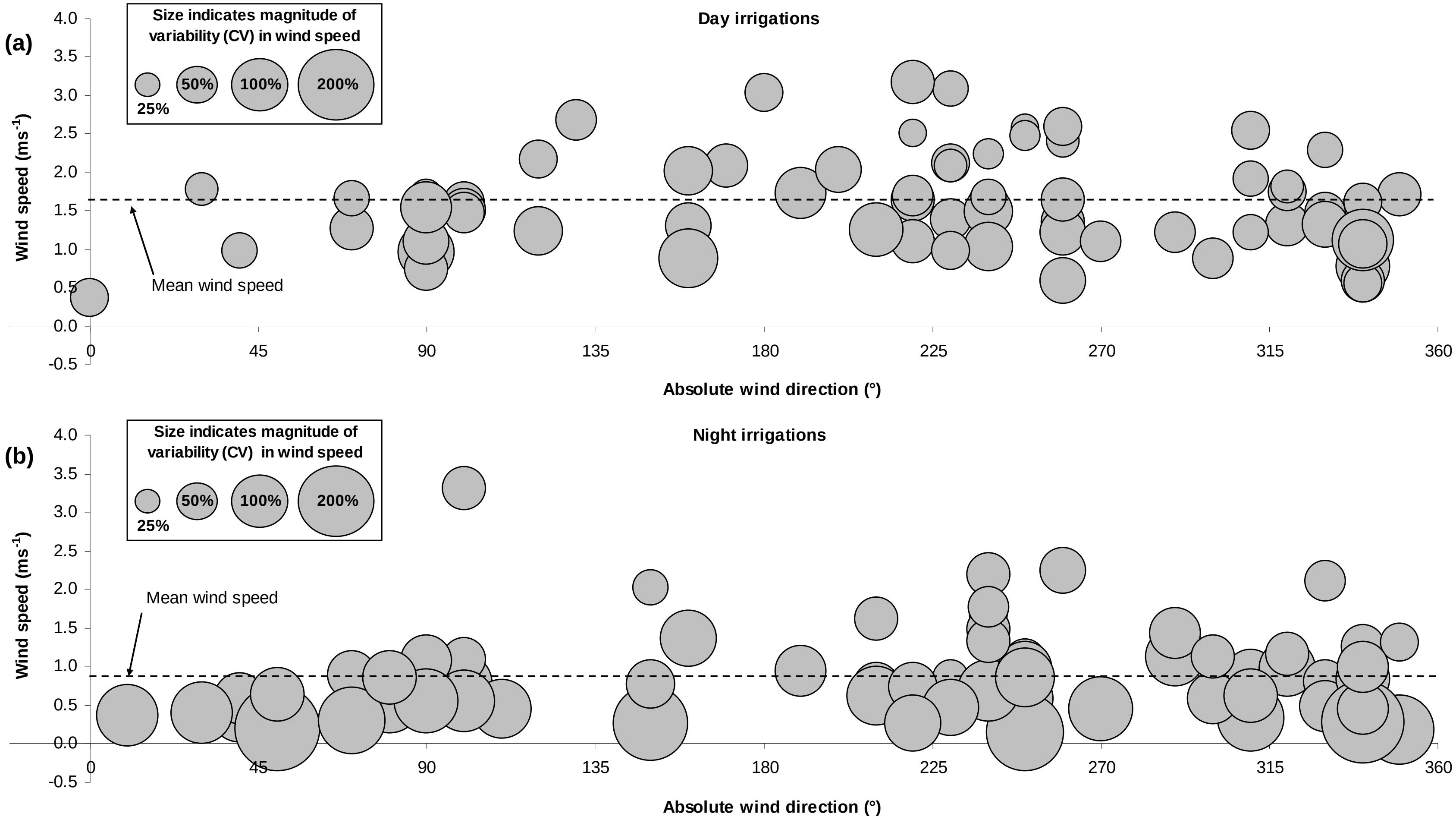


Figure 7.1 Summary of wind conditions during each of the 68 scheduled daytime (a) or night time (b) irrigation events showing mode wind direction, mean wind speed and coefficient of variation (CV) of wind speed.

7.3.2. Parameterisation of the TRAVGUN-TRAVELLER model

Operation of the TRAVGUN-TRAVELLER model required the individual components to be parameterised for the each of the 128 equipment and management scenarios.

A database of wind affected wetted patterns were generated with the TRAVGUN model using the best fit calibration for a Nelson Big Gun SR150® fitted with a 25.4 mm taper nozzle as described in Section 4.4.1. This database comprised of a set of wetted patterns for each of the four selected sector angles (180°, 210°, 240° and 270°). The wetted patterns were generated for wind speeds of 0-10 m s^{-1} (at 1 m s^{-1} intervals) and for all wind directions (at 10° intervals). Note that the maximum wind speed permitted in TRAVGUN is 5.5 m s^{-1}; wetted patterns generated at this wind speed were therefore assumed to represent those for wind conditions of 6 m s^{-1} and above.

The parameters for the TRAVELLER model were defined for the scenarios described in Section 7.1. Sector angles (180°, 210°, 240° and 270°) and lane spacings (50 m, 60 m, 70 m and 80 m) were entered directly into the input text file. The prevailing wind during the growing season was calculated for all the climate data. This was used to determine the required field orientation relative to the prevailing wind (0°, 45°, 90° and 135°). The dates of the scheduled irrigation applications derived using WaSim were then used to determine the start times of the first pull of each irrigation event (assuming a start time of 07:00 hours for day time irrigation and 19:00 hours for night time irrigation). Subsequent pulls were assumed to commence 24 hours after the start of the previous pull. The raingun flow rate was calculated from application rates and the wetted areas observed in the TRAVGUN-generated wetted patterns. This flow rate was used in combination with the relevant lane spacing to determine the raingun pull speed in order to apply the scheduled irrigation depth to the simulated field area. Finally, data files were generated with the appropriate wind speed and direction data for each of the 13 years of climate data.

7.3.3. Parameterisation of the Carrot Calculator and carrot quality models

Operation of the Carrot Calculator and the carrot quality models required parameterisation of the components for a typical carrot production system in the UK.

All model runs assumed a maincrop of carrot variety Nairobi sown on the 1st April in a loamy sand for harvest on the 1st October and attaining a maximum root depth of 0.4 m. The planting arrangement was four triple rows in a bed on 2 m wheel centres (Figure 7.2) with plant spacing within a row assumed to be 32 mm and an emergence rate of 67%. This arrangement resulted in a plant density of 125.6 plants m^2 (the design density for variety Nairobi is typically 110-160 plants m^2).

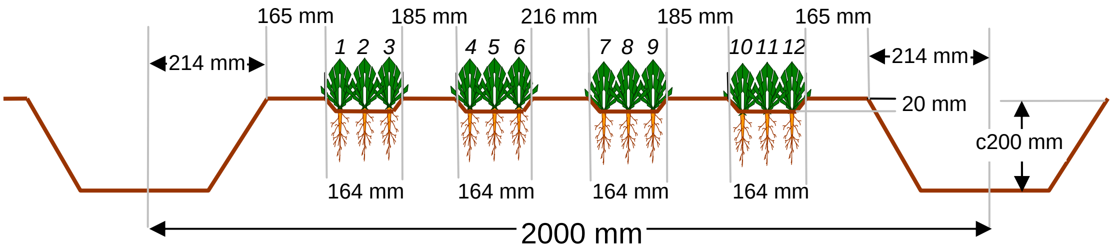


Figure 7.2 *Typical carrot planting arrangement of four triple rows in a bed on 2 m wheel centres used for Carrot Calculator crop growth simulations.*

The pesticide, nutrient and irrigation scheduling regimes were assumed to be non-limiting to production; only water availability due to non-uniform irrigation was assumed to limit crop growth. The soil parameters were defined to match the loamy sand parameters provided in WaSim, using representative values for the soil type provided in the Carrot Calculator model, where required (Table 7.5).

Table 7.5 *Soil parameters used for Carrot Calculator crop growth simulations.*

Parameter	Values
Soil type	Loamy sand
pH	7.0
Laboratory bulk density (g cm^{-3})	1.05*
Field bulk density (g cm^{-3})	1.50
Soil structure score (1-10)	10*
AWC (mm)	45
Profile drainage class (0-4)	1*
Soil evaporation constant	7.05*
Presence of water table	Absent

* denotes estimated values

Irrigation applications through the season falling within each 5 m x 5 m plot in the simulated field area were derived from the TRAVGUN-TRAVELLER outputs using a computer program (Appendix B). Finally, data files were generated with the appropriate temperature, global radiation and rainfall data for each of the 13 years of climate data.

The Carrot Calculator was run using the Red Hot variety calibration and the correction factor derived for site R2004, which had similar agronomic characteristics to those assumed above (see Section 5.4).

The carrot quality model was developed for use under the typical crop production conditions outlined above, thus requiring no further parameterisation.

7.4. Integrated modelling results

For each scheduled irrigation event and for each equipment and management scenario, the spatial heterogeneity in irrigation application was simulated using the TRAVGUN-TRAVELLER model. In total, 8704 individual simulations were conducted. The outputs from this stage of the modelling process were used to:

i) Compare the application uniformity of individual irrigation events against the overall seasonal uniformity;

ii) Evaluate the sensitivity of transect location when measuring irrigation uniformity using catchcans, and;

iii) Investigate the impact of equipment and management strategies on irrigation uniformity.

A limited number of the outputs from the TRAVGUN-TRAVELLER model were then selected as inputs to the crop growth modelling stage. Carrot yield and quality were simulated using the Carrot Calculator and carrot quality models for a crop grown under these selected irrigation conditions in order to:

i) Examine the impact of non-uniform irrigation throughout the season on crop yield and quality;

ii) Investigate the impact of variations in irrigation uniformity during a growing season on crop production, and;

The findings relating to each of these five areas are presented in the following sections.

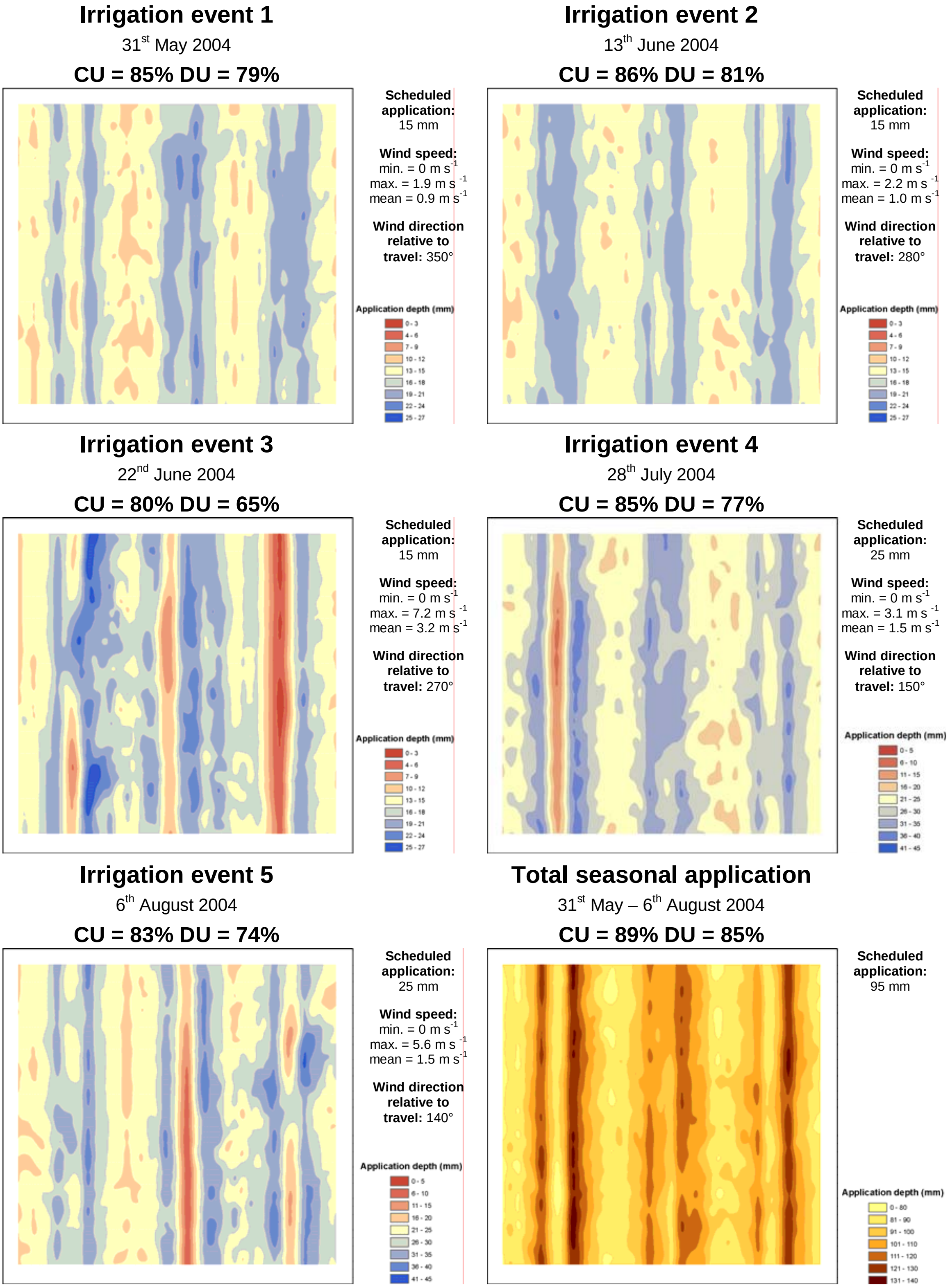
7.4.1. Comparing the uniformity of individual irrigation events to seasonal uniformity

A common approach to assess irrigation performance is to use the seasonal application uniformity – i.e. summing the irrigation applications to each measurement area over the season. However, this can be misleading since random variations in non-uniformity during specific irrigation events can be masked by the process of accumulating irrigation applications over the season.

To examine this issue, the application uniformity (CU and DU) of individual irrigation events were compared to the seasonal uniformity using a typical raingun configuration (field orientation = 90° to prevailing wind, lane spacing = 70 m, sector angle = 270°, day time irrigation) (Table 7.6 and Figure 7.3). In these examples, the overall seasonal application uniformity was consistently higher than the uniformity of any of the individual irrigation events during the season (with the exception of R2001, which probably received insufficient irrigation events to observe any cumulative effect on uniformity). This implies that estimates of irrigation performance based solely on the seasonal application could significantly underestimate the impact of non-uniformity on crop production.

Table 7.6 *Variations between single irrigation event application uniformity and seasonal uniformity using a typical raingun configuration (field orientation = 90° to prevailing wind, lane spacing = 70 m, sector angle = 270°, daytime irrigation) during five selected years.*

Irrigation event	**CU (%)**					**DU (%)**				
	I2001	R2001	I2002	I2003	R2004	I2001	R2001	I2002	I2003	R2004
1	84.5	81.5	85.5	85.4	85.4	76.5	77.3	78.2	79.7	79.4
2	84.8	84.0	85.2	86.3	86.3	75.7	78.3	76.5	80.6	80.8
3	85.3		85.0	84.4	79.8	78.7		77.5	77.5	65.0
4	85.9		86.8	85.3	84.6	80.3		80.0	78.0	77.4
5			84.6	86.4	82.8			77.5	79.0	73.8
6			84.0	86.4				77.9	79.3	
7			86.8	84.8				80.4	79.0	
8			84.4	85.9				78.1	80.0	
9			82.6	85.2				74.6	79.4	
10				85.6					79.3	
11				85.4					78.9	
Mean	**85.1**	**82.8**	**85.0**	**85.6**	**83.8**	**77.8**	**77.8**	**77.9**	**77.3**	**75.3**
Seasonal	**87.8**	**83.2**	**88.5**	**89.0**	**89.1**	**83.0**	**78.2**	**84.1**	**84.1**	**84.7**



Irrigation event 1

31st May 2004

CU = 85% DU = 79%

Scheduled application: 15 mm

Wind speed: min. = 0 m s^{-1} max. = 1.9 m s^{-1} mean = 0.9 m s^{-1}

Wind direction relative to travel: 350°

Irrigation event 2

13th June 2004

CU = 86% DU = 81%

Scheduled application: 15 mm

Wind speed: min. = 0 m s^{-1} max. = 2.2 m s^{-1} mean = 1.0 m s^{-1}

Wind direction relative to travel: 280°

Irrigation event 3

22nd June 2004

CU = 80% DU = 65%

Scheduled application: 15 mm

Wind speed: min. = 0 m s^{-1} max. = 7.2 m s^{-1} mean = 3.2 m s^{-1}

Wind direction relative to travel: 270°

Irrigation event 4

28th July 2004

CU = 85% DU = 77%

Scheduled application: 25 mm

Wind speed: min. = 0 m s^{-1} max. = 3.1 m s^{-1} mean = 1.5 m s^{-1}

Wind direction relative to travel: 150°

Irrigation event 5

6th August 2004

CU = 83% DU = 74%

Scheduled application: 25 mm

Wind speed: min. = 0 m s^{-1} max. = 5.6 m s^{-1} mean = 1.5 m s^{-1}

Wind direction relative to travel: 140°

Total seasonal application

31st May – 6th August 2004

CU = 89% DU = 85%

Scheduled application: 95 mm

Figure 7.3 *Variations between single irrigation event spatial application uniformity and seasonal uniformity (showing CU and DU) using a typical raingun configuration for all irrigation events during R2004. Raingun characteristics: field orientation = 90° to prevailing wind; lane spacing = 70 m; sector angle = 270°; daytime irrigation.*

These findings support previous research (e.g. Pair, 1968) and observations made during this study (Section 4.3.3). In addition, the findings appear to endorse the perception of many growers that low application uniformity during a single event is relatively unimportant since its impacts are mitigated by different spatial application patterns during subsequent irrigations. However, as noted in Chapter 6, water shortages (or indeed excesses) during critical growth stages could be highly influential in determining final carrot crop yields and particularly for root quality. Therefore this perception that non-uniformity during the season is not significant may be incorrect and indeed may have implications for crop production that are not fully appreciated by growers. Consequently, it was necessary to examine not only the overall impact of systematic application non-uniformity on crop production (using seasonal uniformity measures) but also the impact of random variations in irrigation uniformity during the growing season (Sections 7.4.4 and 7.4.5).

7.4.2. Evaluating the sensitivity of catchcan transect location when measuring irrigation uniformity

Referring to Figure 7.3, the model outputs confirm that there can be significant application non-uniformity both across and down a field due to short-term variations in wind conditions during irrigation (e.g. in irrigation event 3). This has implications for the measurement of irrigation uniformity using catchcan transects across a field – for example how accurately does a measurement taken during a particular irrigation event across a particular transect location reflect the overall uniformity in the field?

To examine this issue, the application uniformity was calculated from transect locations at 5 m intervals down the field for the five irrigation events shown in Figure 7.3 (a total of 40 transects per irrigation event). CU and DU were calculated for all transects within the calculation area.

CU and DU varied considerably as a result of the catchcan transect location and the irrigation event for which it was recorded (Table 7.7). Within the 200 possible catchcan transects calculated during the season, the CU varied from 78% to 88% with a coefficient of variation of 3% and the DU varied from 63% to 84% with a coefficient of variation of 8%. For different transect locations during individual events, CU typically varied by about 5%, with a coefficient of variation of 1-2% and DU typically varied by about 8%, with a coefficient of variation of 2-4%. The low coefficients of variation indicated that uniformity calculated at the majority of transect locations/irrigation events might provide a reasonable representation of the system uniformity. However, the relatively wide observed range of CU and particularly DU values indicated that any in-field evaluations of system performance relying on a single catchcan transect must be interpreted with care.

Table 7.7 *Variation in CU and DU depending on catchcan transect location in field and irrigation event for which uniformity was calculated. Data calculated for climate data R2004 using a typical raingun configuration (field orientation = 90° to prevailing wind; lane spacing = 70 m; sector angle = 270°; daytime irrigation).*

Irrigation event	**CU (%)**			**DU (%)**		
	Minimum	**Maximum**	**CV (%)**	**Minimum**	**Maximum**	**CV (%)**
1	82.9	87.9	1.6	76.1	82.7	2.0
2	85.2	88.3	0.9	78.4	84.1	1.7
3	78.0	82.7	1.7	62.5	72.5	3.7
4	81.7	87.2	1.4	74.4	82.0	2.2
5	81.0	85.6	1.5	70.5	80.7	3.9
All	**78.0**	**88.3**	**3.1**	**62.5**	**84.1**	**7.7**

7.4.3. Impact of equipment and management strategies on irrigation uniformity

The impact of equipment and management strategies on application uniformity was investigated by examining the CU and DU of the spatial application patterns generated by the TRAVGUN-TRAVELLER model. The CU and DU for each scenario were calculated using a computer program (Appendix B).

Figure 7.4 presents four outputs from these simulations which illustrate the impact of lane spacing on application uniformity for a typical irrigation event using climate data R2004 and a typical raingun configuration (field orientation = 90° to prevailing wind, lane spacing = 70 m, sector angle = 270°, day time irrigation). It is apparent that lane spacing has a considerable impact on application uniformity. Narrow spacing (e.g. 50 m) tends to result in excessive applications in the overlap region and wide spacing (e.g. 80 m) tends to result in insufficient overlap between pulls.

Figure 7.5 and Figure 7.6 demonstrate the effect of changing the lane spacing and sector angle on application uniformity under the prevailing wind conditions during irrigations[8].

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[8] Note that the effect of changing field orientation relative to prevailing wind and day versus night irrigation is intrinsically included in this analysis.

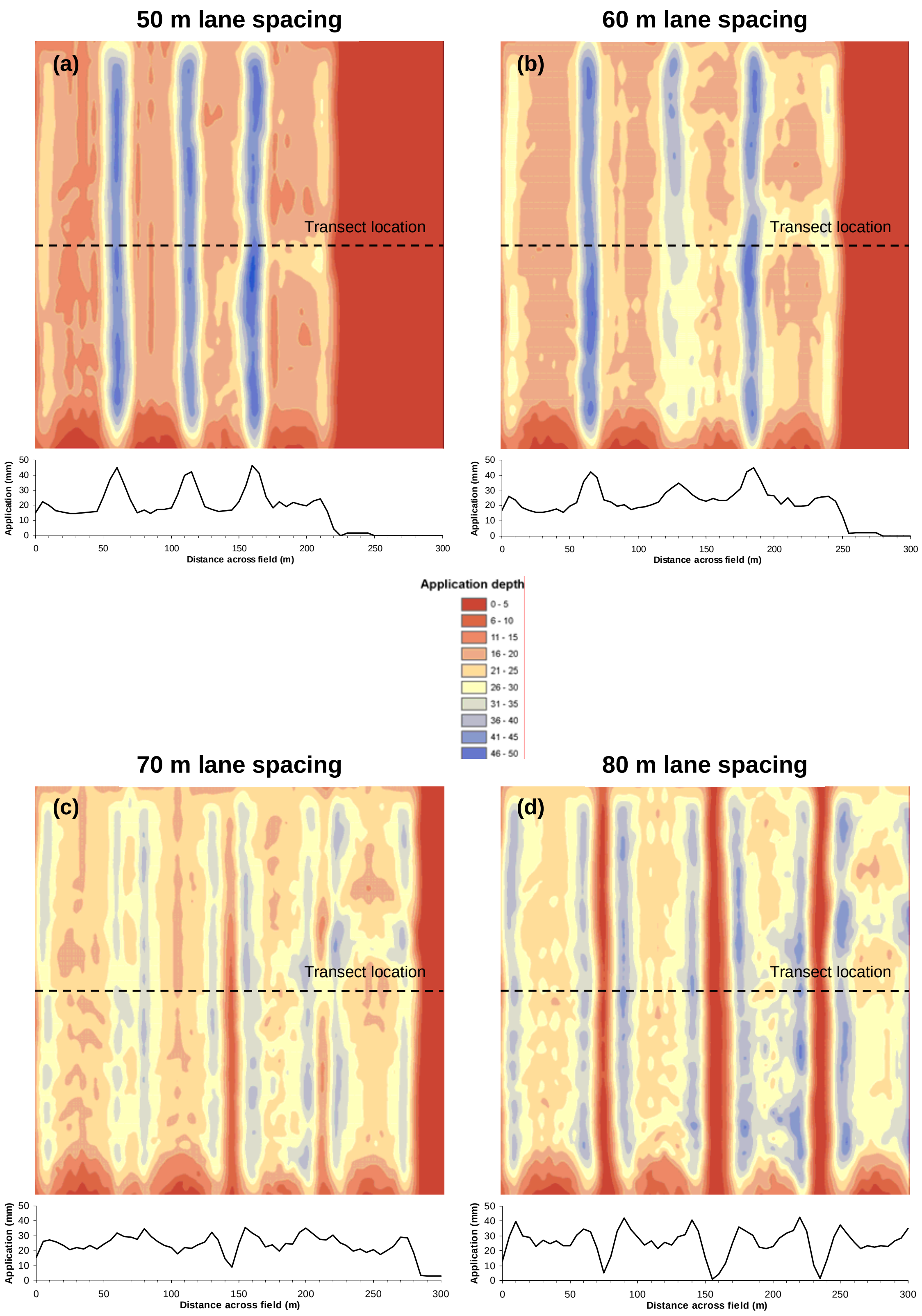

Figure 7.4 *Simulated field level irrigation application and example transects for lane spacings of: 50 m (a); 60 m (b); 70 m (c) and 80 m (d). Field orientation to prevailing wind = 90°, sector angle = 270°, daytime irrigation. Irrigation event starts at 07:00 on 6th August using R2004 climate data. Mean wind speed = 1.5 m s^{-1}, min. wind speed = 0 m s^{-1}, max. wind speed = 5.6 m s^{-1}, prevailing wind direction = 140° to travel direction.*

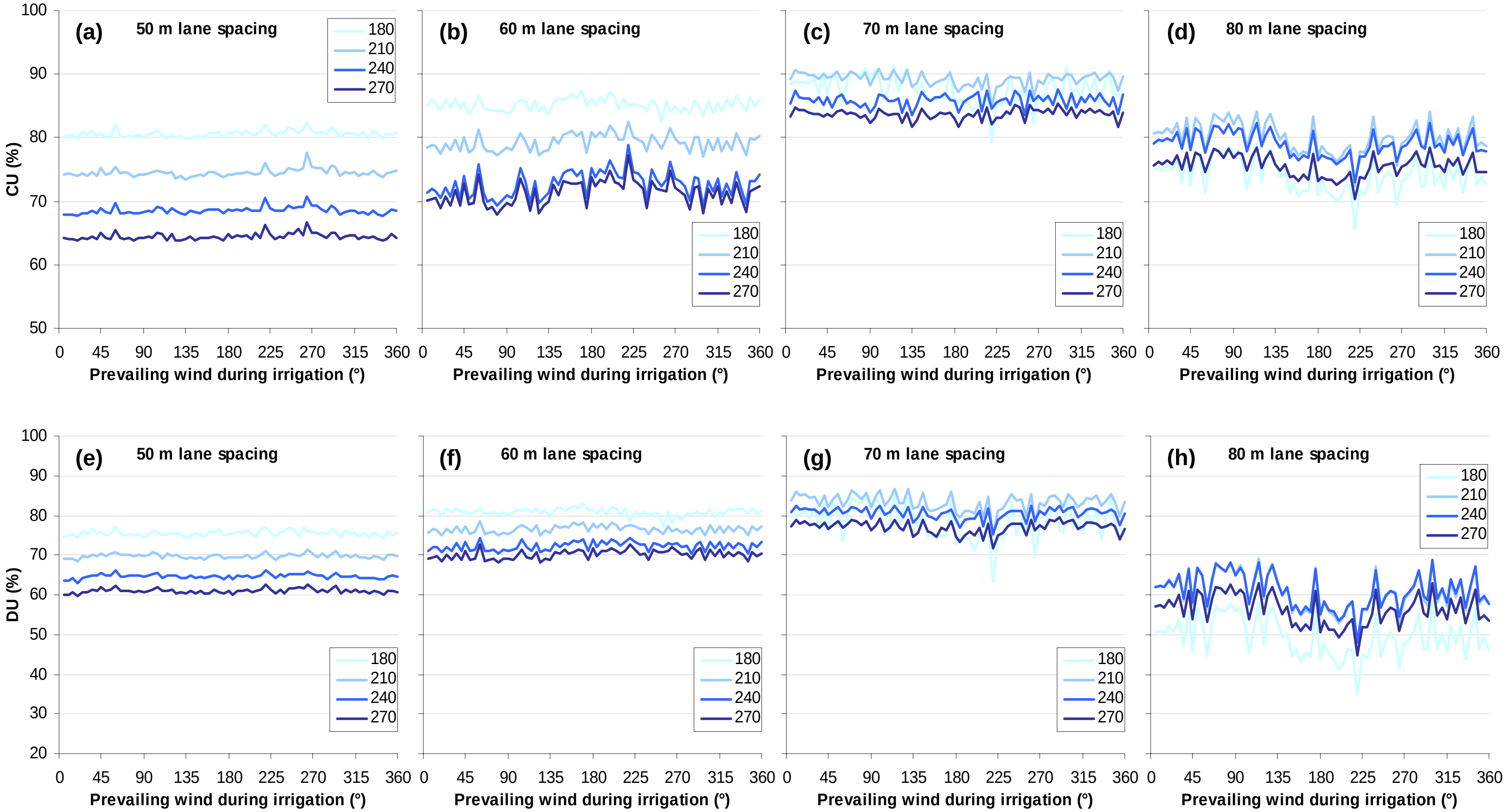

Figure 7.5 *Impact of lane spacing and sector angle on CU (a) – (d) and DU (e) – (h) for the prevailing wind directions experienced during simulated irrigation events (averaged over all wind speeds).*

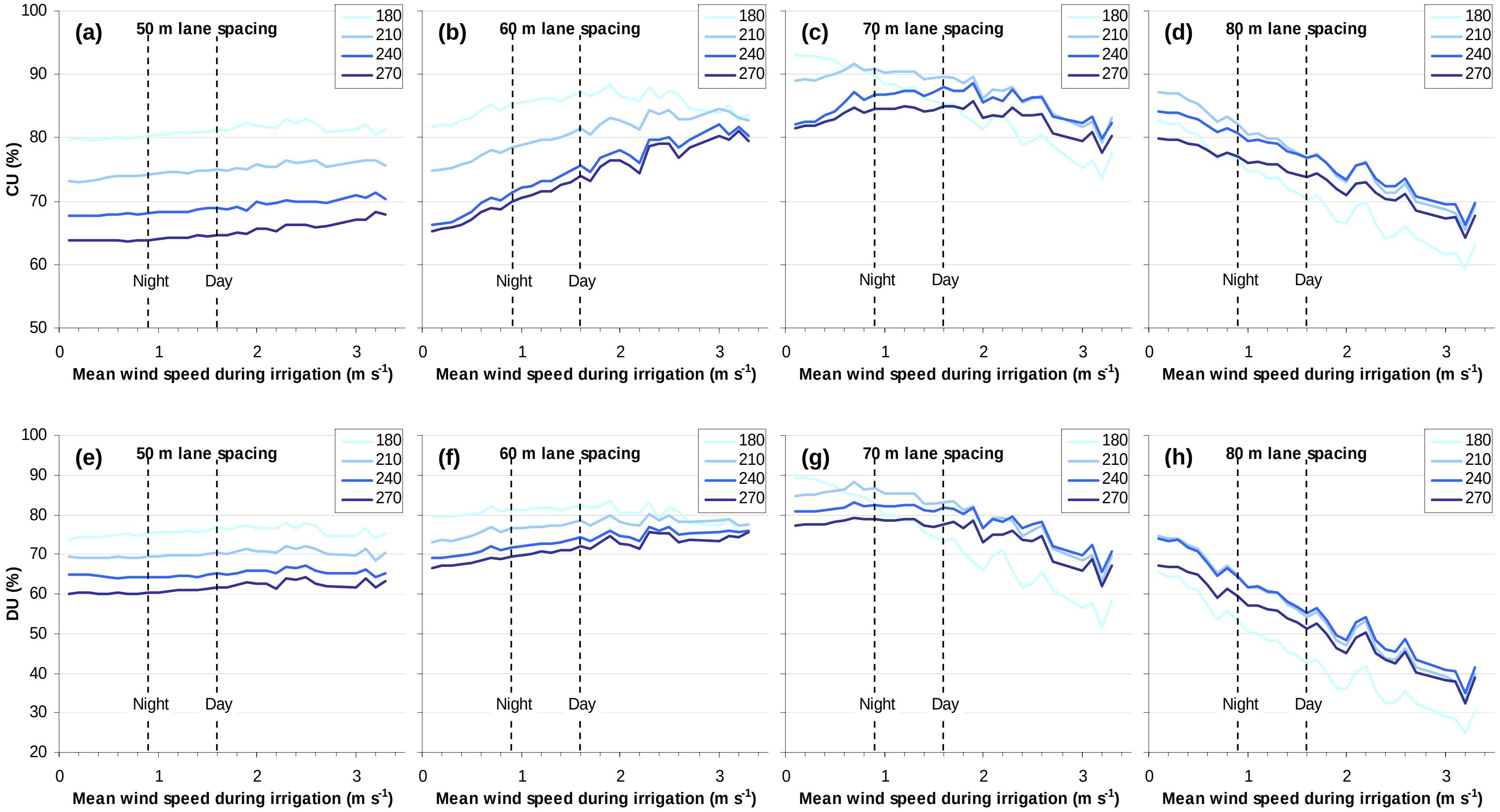

Figure 7.6 *Impact of lane spacing and sector angle on CU (a) – (d) and DU (e) – (h) for the range of mean wind speeds experienced during simulated irrigation events (averaged over all wind directions). Mean day and night wind speeds are also shown.*

The application uniformity for each of the simulations varied considerably as a result of wind conditions and the selected irrigation strategy– from very high (CU of >90% and DU of >85%) to very low (CU of <60% and DU of <25%), with the majority of simulations returning CUs of 75-80% and DUs of 65-70%.

The impacts of changing the selected equipment and management strategies on application uniformity are discussed below.

Field orientation

The effect of the prevailing wind direction during irrigation was relatively limited compared with previous research (e.g. Schull and Dylla, 1976a,b; Oakes and Rochester, 1981; Musa, 1988; and Al-Naeem, 1993), although its significance increased with wider lane spacing. At 50 m lane spacing, there was almost no discernable effect on uniformity. At 60 m lane spacing, there were indications that winds parallel to the travel direction marginally increased both CU and DU, probably by reducing the extent of excessive overlap between pulls. However, at wider lane spacing (particularly 80 m), it was apparent that prevailing winds parallel to the travel direction reduced application uniformity by increasing the extent of under-irrigated areas in the overlap region. At 80 m lane spacing, CUs and DUs were typically reduced by about 5% and 10% respectively as a result of parallel compared to perpendicular winds.

Lane spacing

Travel lane spacing had a considerable effect on application uniformity, supporting studies by many other researchers (e.g. Schull and Dylla, 1976a,b; Oakes and Rochester, 1981; Hipperson, 1985; Musa, 1988; Al-Naeem, 1993; Grose, 1999). At a lane spacing of 50 m, uniformity was generally low (CU of 65-80%, DU of 60-75%), and tended to marginally increase with greater wind speeds. The majority of non-uniformity at this lane spacing was due to over-application in the overlap region between pulls (indicated by a relatively high DU:CU ratio and greater rate of change in CU with increasing wind speed). At 60 m spacing, uniformity was generally improved (CU of 65-85%, DU of 65-80%). Wind speeds of up to about 2 m s^{-1} at this lane spacing tended to increase application uniformity. Higher wind speeds tended to slightly reduce uniformity.

Similarly to 50 m spacing, the majority of non-uniformity at 60 m spacing was due to over-application in the overlap region.

A lane spacing of 70 m provided generally high application uniformity (CU of 75-90% and DU of 55-85%). However at this lane spacing, only very slight wind speeds (<1 m s^{-1}) tended to increase uniformity. At higher wind speeds, uniformity decreased relatively rapidly due to under-application in the overlap region (indicated by a slightly lower DU:CU ratio and a greater rate of change in DU with increasing wind speed). A lane spacing of 80 m resulted in variable but generally low uniformity (CU of 65-85%, DU of 30-70%). Any increase in wind speed from still conditions resulted in a rapid decrease in uniformity, primarily as a result of large areas of under-application in the overlap region. As discussed earlier, wider lane spacing also resulted in increased susceptibility of the application uniformity to wind direction.

Overall, at wind speeds of less than about 2 m s^{-1}, a 70 m lane spacing appeared to result in maximum application uniformity. At higher wind speeds, there were indications that lane spacing should be reduced to 60 m, but only where a suitable sector angle was selected.

Sector angle

Changing the raingun sector angle had a considerable effect on application uniformity. Increasing the sector angle from 180° to 270° resulted in considerable reductions in application uniformity at narrow lane spacings (50 m and 60 m) under most wind conditions. However, the application uniformity using smaller sector angles (180° and 210°) became increasingly susceptible to higher wind speeds as lane spacing was increased. Larger sector angles (240° and 270°) tended to give lower uniformity at low wind speeds, but were less susceptible to wind effects at higher wind speeds. There was little discernable effect of prevailing wind direction on application uniformity using different sector angles.

Overall, the optimal sector angle for narrow lane spacings was 180°, although there was an indication that increasing the sector angle to 210° was beneficial when wind speeds exceeded about 3 m s^{-1} at 60 m spacing. At wider lane spacings, a sector angle of 210°

was optimal for wind speeds of less than about 2 m s^{-1}. A marginal benefit could be gained by increasing the sector angle to 240° at higher wind speeds.

These findings are consistent with the research of Al-Naeem (1993), Turker (1998) and Grose (1999) and the industry advice from Swallow (2001), Keller and Bleisner (1990) and Growcom (2004a).

Day versus night irrigation

The mean wind speed during each irrigation had a considerable effect on application uniformity. Gentle winds tended to slightly increase uniformity from still conditions (particularly at narrow lane spacings). However, higher wind speeds caused a rapid decline in uniformity which was particularly pronounced at wide lane spacings. Observations from the 13 seasons of climate data indicated that night time wind speeds were typically almost half those during the day. Consequently, simulations of night time irrigation tended to result in slightly increased uniformity over day irrigations. These findings agreed with general industry advice to irrigate at night where possible (e.g. Bailey, 1987; Millar, 2002; Growcom, 2004b).

7.4.4. Impact of non-uniform irrigation throughout the season on crop yield and quality

The impact of non-uniform irrigation throughout the season on crop yield and quality was investigated using the Carrot Calculator and carrot quality models. Due to limitations in processing time, it was not possible to simulate the impact on crop yield and quality of all irrigation equipment and management scenarios modelled for each of the thirteen years of climate data (1,664 simulations). Consequently, only a sub-set of the data was selected for analysis (40 simulations). These comprised of eight irrigation strategy scenarios which encompassed a wide range of application uniformities (Table 7.8). These irrigation strategies were modelled for five years of climate data: two years of relatively high irrigation requirement (I2002 and I2003), two years of relatively low irrigation requirement (I2001 and R2001) and one with intermediate demands (R2004) (Table 7.4).

Table 7.8 *Equipment and management strategy scenarios selected for simulation using the Carrot Calculator and carrot quality models, showing CU and DU range for all irrigation events during the five selected years.*

Field orientation to prevailing wind	Lane spacing	Sector angle	Time of irrigation	CU range for all irrigation events during selected years	DU range for all irrigation events during selected years
90°	50 m	180°	Day	79-84%	73-80%
90°	60 m	180°	Day	81-90%	74-86%
90°	80 m	180°	Day	61-83%	27-65%
90°	70 m	210°	Day	81-93%	67-90%
90°	80 m	210°	Day	66-87%	34-75%
90°	50 m	270°	Day	63-67%	58-64%
90°	60 m	270°	Day	65-80%	67-76%
90°	70 m	270°	Day	80-87%	65-81%

The irrigation application outputs from the TRAVGUN-TRAVELLER model for these 40 simulations were converted into the appropriate file format for input to the Carrot Calculator. Crop yield and quality in each 5 m x 5 m plot of the simulated field area was then modelled using the Carrot Calculator and carrot quality models.

Figure 7.7 and Figure 7.8 illustrate the impact of two contrasting irrigation scenarios on seasonal application uniformity and the consequences for carrot crop yield and quality in a relatively dry year (I2003).

The low uniformity scenario (90° to prevailing wind, 80 m lane spacing, 180° sector angle, daytime irrigation) resulted in large areas in the overlap regions between pulls which were under-irrigated (some areas receiving almost no irrigation) and other areas receiving almost twice the planned application. Consequently, uniformity was generally low. The CU and DU for the eleven irrigation events during the season was typically 66-76% and 37-53% respectively, with a seasonal CU of 74% and DU of 49%. As a result of this variation in irrigation application, total crop yield over the calculation area varied from 90 t ha^{-1} in the under-irrigated areas to 135 t ha^{-1} with a mean of 129 t ha^{-1} (CV = 9%). More importantly, quality losses were as high as 38% in the under-irrigated areas and averaged 10% overall with a CV of 85%. The majority of these quality losses were attributed to poor establishment and uniformity (6%) and root morphology (4%) with very little loss to scab. This resulted in marketable yields of 45-102 t ha^{-1} and an overall mean marketable yield of 94 t ha^{-1} (CV = 16%).

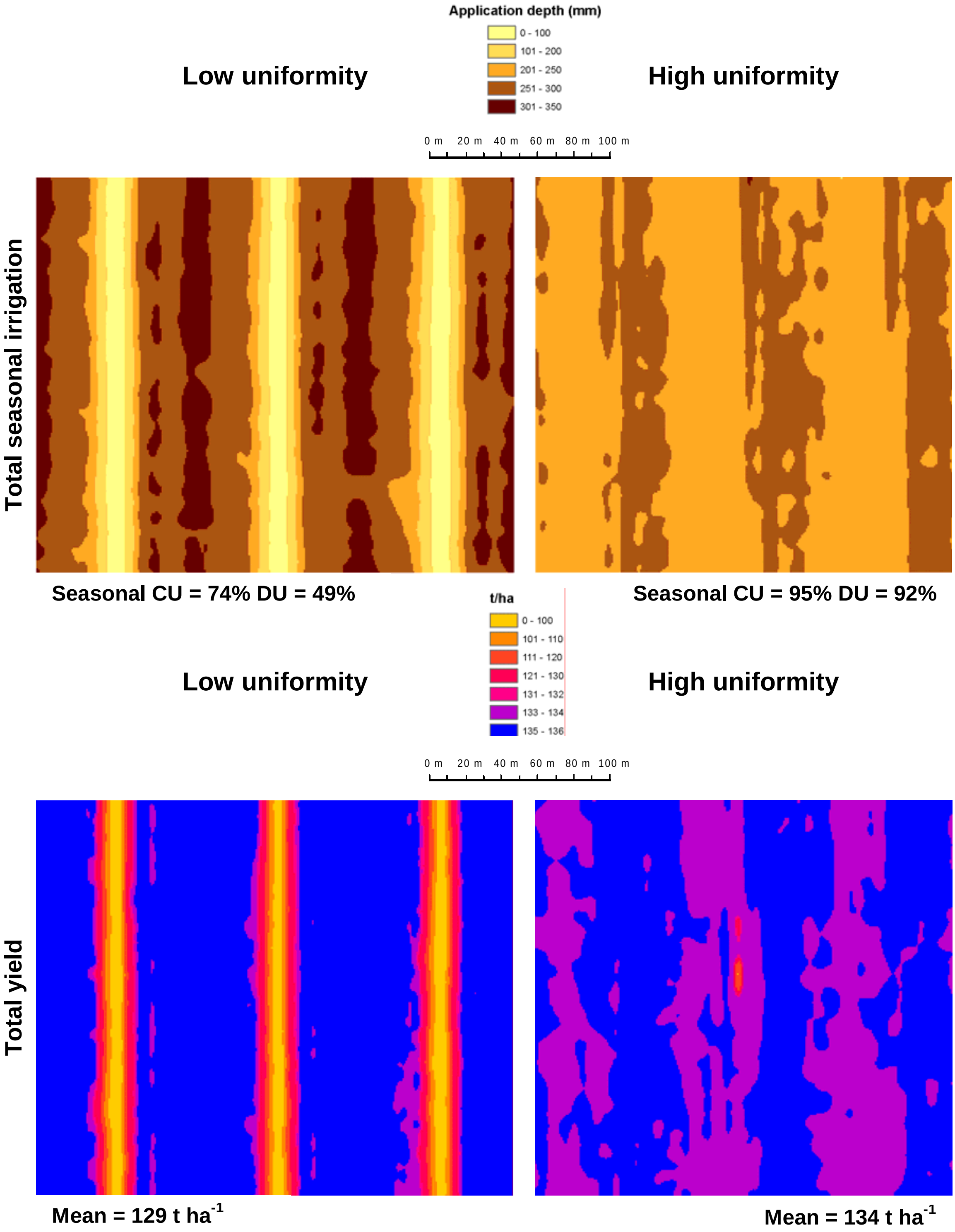

Figure 7.7 *Illustration of the impact of two contrasting irrigation scenarios on seasonal application uniformity and total carrot crop yield for a dry year (I2003).*

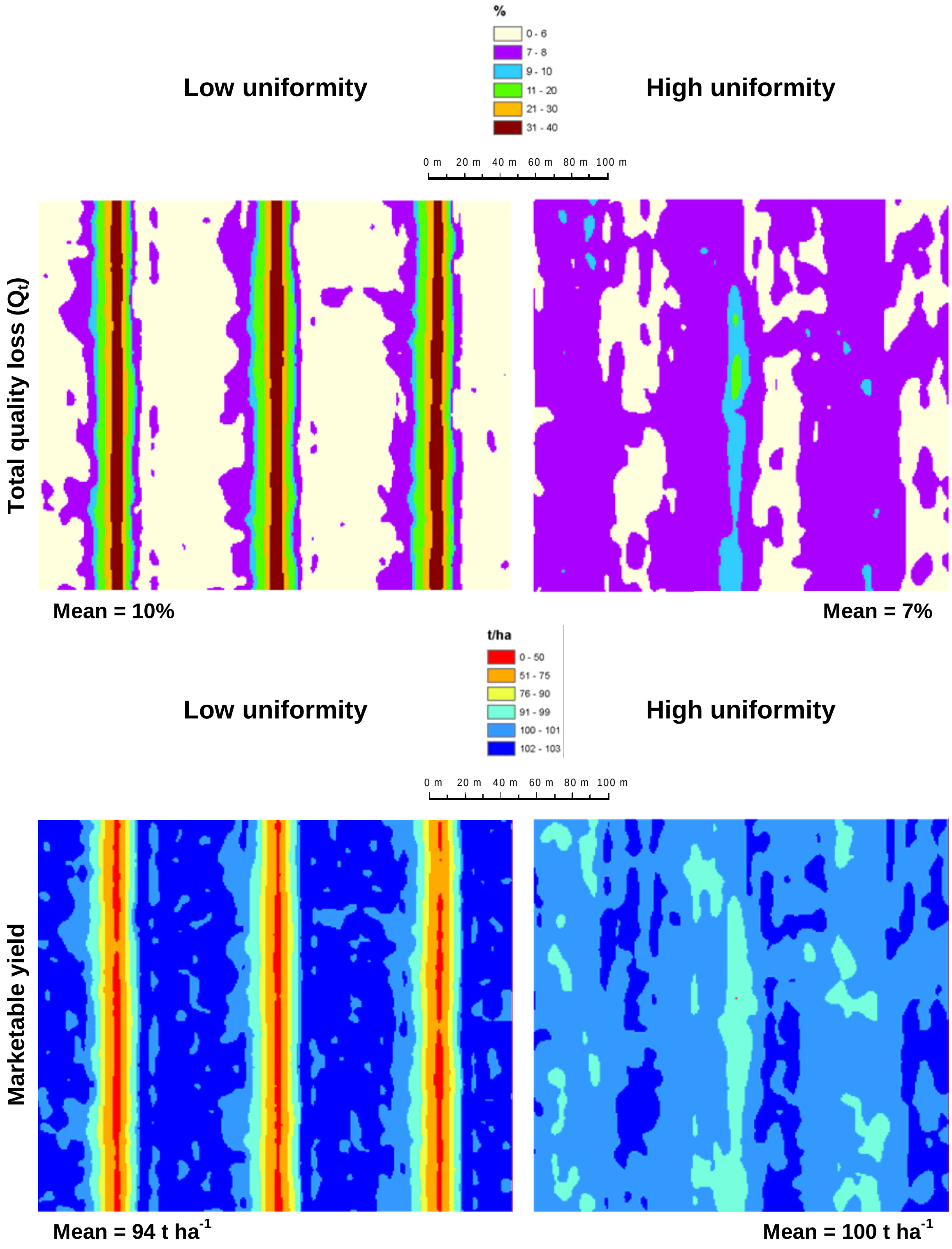

Figure 7.8 *Illustration of the impact of two contrasting irrigation scenarios on carrot crop quality losses and marketable yield for a dry year (I2003).*

In contrast, the high uniformity scenario (90° to prevailing wind, 70 m lane spacing, 210° sector angle, daytime irrigation) had fewer areas which received over or under irrigation. Minimum applications were more than half the planned depths and maximum applications were less than 1.8 times the planned depths. The CU and DU during the eleven irrigation events was typically 87-93% and 80-90% respectively, with a seasonal CU of 95% and DU of 92%. As a result of this high application uniformity, yields were generally higher and less variable than in the low uniformity example. Total crop yield varied from 132-135 t ha^{-1} with a mean of 134 t ha^{-1} (CV = 0.2%). Maximum quality losses observed were about 11% and averaged 7% overall with a CV of 11%. Again, the majority of these quality losses were attributed to poor establishment and uniformity (4%) and root morphology (3%) with no scab losses. This resulted in marketable yields of 94-102 t ha^{-1} and an overall mean marketable yield of 100 t ha^{-1} (CV = 1%).

The impact of non-uniform irrigation on crop production over the five years of climate data was examined by correlating total crop yields, marketable yields and premium root yields against seasonal uniformity (CU and DU) for the selected irrigation scenarios (Figure 7.9 – note that only data relating to I2001, I2002 and I2003 are shown for clarity).

With reference to Figure 7.9, three important points can be observed:

i) The impact of irrigation non-uniformity on crop production is highly dependant on the climate for crop growth during the season. In years of relatively low irrigation requirement (such as I2001) even very non-uniform irrigation throughout the season resulted in relatively small losses (0.4% reduction in total yield, 1.6% in marketable yield and 2.5% in premium root yield from the most uniform irrigation scenario). However, in years of relatively high irrigation demand (such as I2002 and I2003), low irrigation uniformity resulted in reductions of up to 4.0% in total yield, 7.8% in marketable yield and 10.5% in premium root yield from the most uniform irrigation scenario;

ii) Root quality responds more strongly to changes in irrigation uniformity than yield alone (see above), and;

iii) Increasing seasonal application uniformity beyond a CU and DU of about 85% results in little appreciable increase in root yield or quality.

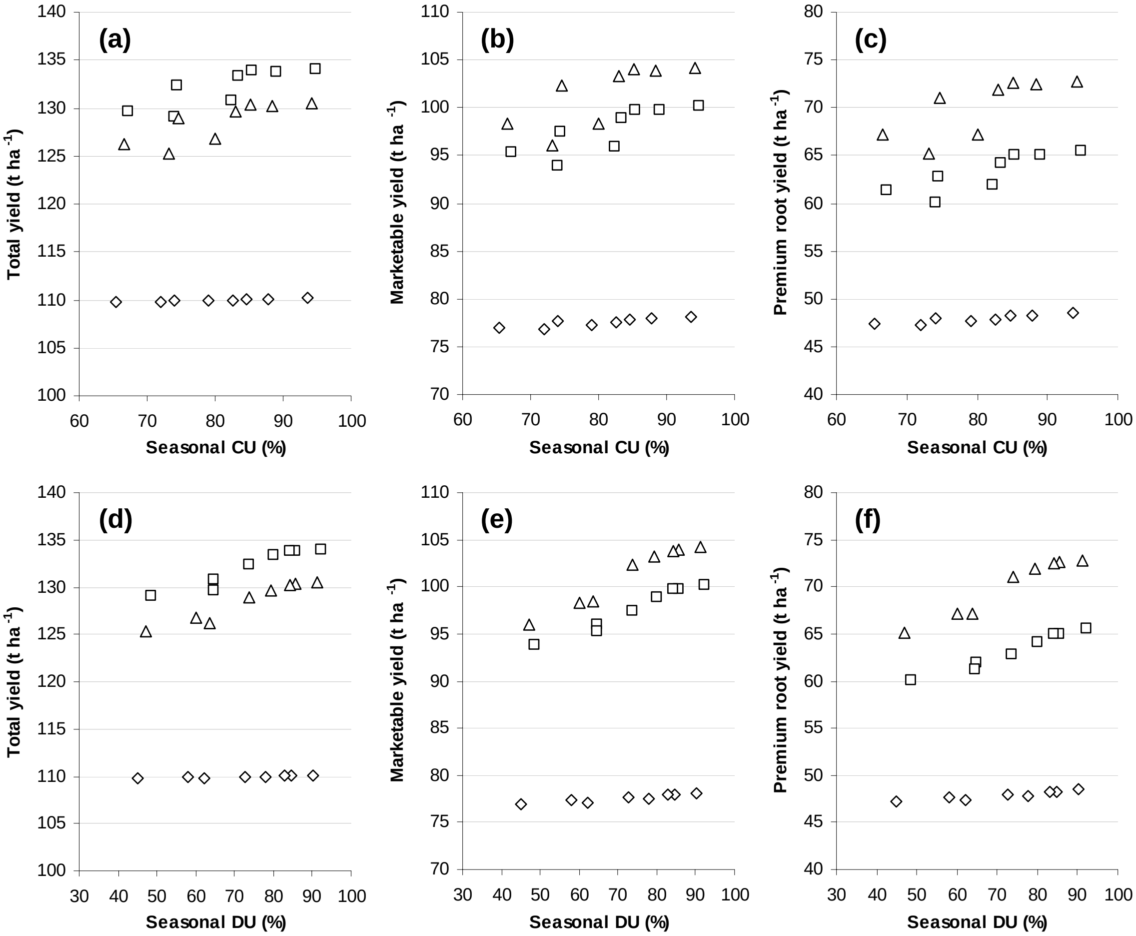

__Figure 7.9__ The impact irrigation non-uniformity on carrot crop production showing the relationship between CU and total crop yield (a), marketable yield (b) and premium root yield (c) and the relationship between DU and total crop yield (d), marketable crop yield (e) and premium root yield (f) for three differing seasons. Squares represent I2003, triangles I2002 and diamonds I2001).

The field level yield reductions observed above appear quite conservative. However, they are likely to be highly significant to growers, particularly when considered in the context of the typically small profit margins associated with commodity vegetable crops such as carrots. Furthermore, when consideration is given to the relatively small extent of areas which are sub-optimally irrigated and the effects of rainfall through the season (which tends to reduce the effects of non-uniform irrigation) the losses appear reasonable. Indeed, the effect of unseasonal rainfall was cited by Sanden *et al.* (2000) and Koech (2003) as the primary cause for the lack of correlation they observed between irrigation uniformity and crop production.

The results of this research appear to support UK farm trials by Revaho (2005) which demonstrated a total yield increase of 0.3%, a marketable yield increase of 1.8% and a premium root yield increase of up to 6% for carrot variety Nairobi grown on sandy loam soil in 2004 under sprinkers compared to raingun irrigation. Although uniformity during the season was not recorded, it was assumed that the yield increases were a direct result of the higher uniformity of the sprinkler system.

7.4.5. Impact of variations in irrigation uniformity during a growing season on crop production

The results of the previous section indicated that uniform irrigation application over the whole season is important to carrot crop yield and quality. Comparison to the observed seasonal CU and DU for both site I2003 and I2004 – 90% and 87% for I2003 and 89% and 83% for I2004 respectively – therefore suggested that little total or marketable yield would have been lost due to non-uniform irrigation. However, there were a number of individual irrigation events at both sites which had low application uniformity (CU <70% and DU <60%). This may have reduced crop yields due to the increased sensitivity of the crop to water shortages during particular growth stages (as identified in Chapter 6).

The integrated modelling approach was therefore used to provide a preliminary examination of the impact on crop yield and quality of low application uniformity during critical growth stages (0-9, 9-13, 13-17, 17-21 and 21 weeks after sowing to harvest) for a dry year (I2003). Two scenarios were investigated: the impact of low uniformity in all irrigation events which occurred during each of the growth stages (in a season of otherwise high uniformity); and the impact of a single low uniformity irrigation event during each of the growth stages (in a season of otherwise high uniformity). High and low uniformity for the appropriate irrigation events were simulated using 70 m spacing with 210° sector angle and 80 m spacing with 180° sector angle respectively (field orientation to prevailing wind = 90°, daytime irrigation). Figure 7.10 illustrates the percentage yield losses as a result of these two scenarios from a crop which received high uniformity irrigation throughout the entire growing season in a dry year (I2003).

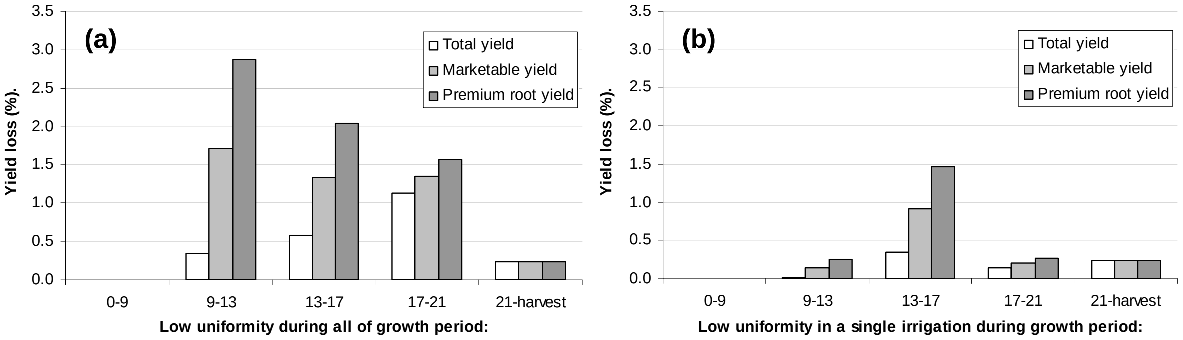

Figure 7.10 *Percentage yield losses from a crop which received high uniformity irrigation throughout the growing season in a dry year (I2003) as a result of low uniformity in all irrigation events during each period of crop growth (a) and a single low uniformity irrigation event during each period of crop growth (b). Note that crop growth periods are in weeks after sowing.*

The first point to observe from this example is that climatic variations during the growing season had a considerable effect on the potential losses which may occur due to low irrigation uniformity at any particular growth period. For instance, in Figure 7.10, no yield losses were observed due to low irrigation uniformity during the first nine weeks of crop growth. This was because there was sufficient rainfall during that period to offset any negative impacts of non-uniform irrigation. Despite these climatic effects, the analysis indicated that low irrigation uniformity during all of the crop growth period 17-21 weeks after sowing resulted in the highest total yield loss (1.1%) from a crop which received high uniformity irrigation. However, low irrigation uniformity during all of the crop growth period 9-13 weeks after sowing resulted in the greatest marketable and premium root yield reduction from a crop which received high uniformity irrigation (1.7% and 2.9% respectively).

The impact of a single low uniformity irrigation event on crop production was lower than the effect of low uniformity irrigation during all of a crop growth period. In addition, the impact of a single low uniformity irrigation event was much more dependent on the climate during the period when it occurred. Consequently, the greatest impact on total, marketable and premium root yield occurred as a result of a single low uniformity irrigation event during the crop growth period 13-17 weeks after sowing. This was because the affected irrigation event in this growth period occurred during a time of high irrigation requirement. The maximum total, marketable and premium root yield losses from a crop which received high uniformity irrigation were 0.3%, 0.9% and 1.5% respectively.

It is therefore clear that the application uniformity of irrigation events during certain growth periods can have a small but appreciable impact on carrot yield, and particularly quality. Relating this to site I2003 suggests that low uniformity during irrigation events 2, 3 and 4 (81, 100 and 118 days after sowing) may have adversely affected both total and marketable yields. Similarly, at site R2004, the low uniformity observed during irrigation event 3 (92 days after sowing) may also have adversely affected total and marketable yields.

Although no research has been carried out to investigate the effects of non-uniform irrigation during different growth periods, these findings are consistent with the results of trials into the effect of droughting carrots at different times by Stiles (2002), Riley and Dragland (1988), Sorensen *et al.* (1997) and Groves and Bailey (1994).

7.5. Other applications of the integrated modelling approach

In order to further demonstrate the potential uses of the integrated modelling approach beyond the investigation of the impact of equipment and management strategies presented in this chapter, two additional examples of its application are considered. Firstly, the approach was employed to investigate the impacts of day-to-day irrigation management decisions on crop production. Secondly, the application of the integrated modelling approach for evaluating the potential impacts of future climate change (particularly variations in wind speed) was investigated. These two examples are presented below.

7.5.1. Impact of irrigation management decisions

Day-to-day irrigation management decisions are likely to have considerable impacts on crop production. However, the magnitude of these impacts is currently unknown. The integrated modelling approach can be used to quantify the impacts of such management decisions on application uniformity and the consequent impacts for crop yield and quality. An example of the application of the integrated modelling approach to this issue is presented below.

Consider a scenario in which a particularly windy period coincides with the date on which an irrigation has been scheduled during a dry part of the season when the carrot crop is particularly sensitive to water stress (i.e. early to mid season). In this situation, a grower must decide whether to irrigate and risk low uniformity (with consequences for crop production), or wait until calmer wind conditions and risk greater crop stress (with other consequences for crop production). The perceived wisdom is that the application of some water, however non-uniform, is likely to be better than none. However, there is currently no way to validate this assumption. Consequently, growers have no evidence to refute claims by the public or the regulatory authorities that they are wasting water through non-uniform applications when irrigating in windy conditions. The integrated modelling approach can be used to investigate and quantify the consequences of these irrigation management choices.

Climate data for a typical dry year (I2003) was manipulated to create scenarios for this example. Firstly, a rainfall event was introduced near the start of the critical crop growth period 9-13 weeks after sowing to bring the soil to field capacity. This ensured that any heterogeneity in soil moisture resulting from previous irrigation events was equalised. Following this rainfall event, no further rain fell for a period of three weeks. The data were then further manipulated to create particularly windy conditions during the four days on which the first irrigation event in this period was scheduled (irrigations were scheduled as outlined in Section 7.3.1). This was achieved by multiplying the original observed wind speed data by a factor of 2-3 to create mean wind speeds for the period 0700-1700 hours of 4.5-6.1 m s^{-1}. Directly after this windy period, wind speeds for the following four days were reduced by a factor of 0-0.4 giving means of 0.8-1.1 m s^{-1}.

Using this manipulated climate data, two scenarios were defined:

i) "Windy" scenario: irrigations are applied when scheduled through the season, including during the period when wind speeds were artificially increased.

ii) "Delay" scenario: before the induced windy period, irrigations are applied as scheduled. However, at this point, the irrigation is delayed by four days until wind conditions are calmer. Because of this delay, more water than would typically be scheduled during this crop growth stage is applied at this irrigation to simulate a typical grower response to the delay (25 mm instead of 15 mm). After this event, irrigations are once again applied as scheduled.

The manipulated climate data and the resulting soil moisture deficits and irrigation applications (defined using WaSim as in Section 7.3.1) for both the windy and delay scenario are presented in Figure 7.11. Note that by delaying the irrigation and applying 25 mm rather than the scheduled 15 mm depth, one fewer irrigation was required during the season for the delay compared to the windy scenario. As a result, 5 mm less irrigation was applied during the season under the delay scenario. However, since all irrigation both before and after the delayed event was applied according to the same scheduling rules as for the windy scenario, a direct comparison between the two is considered to be valid.

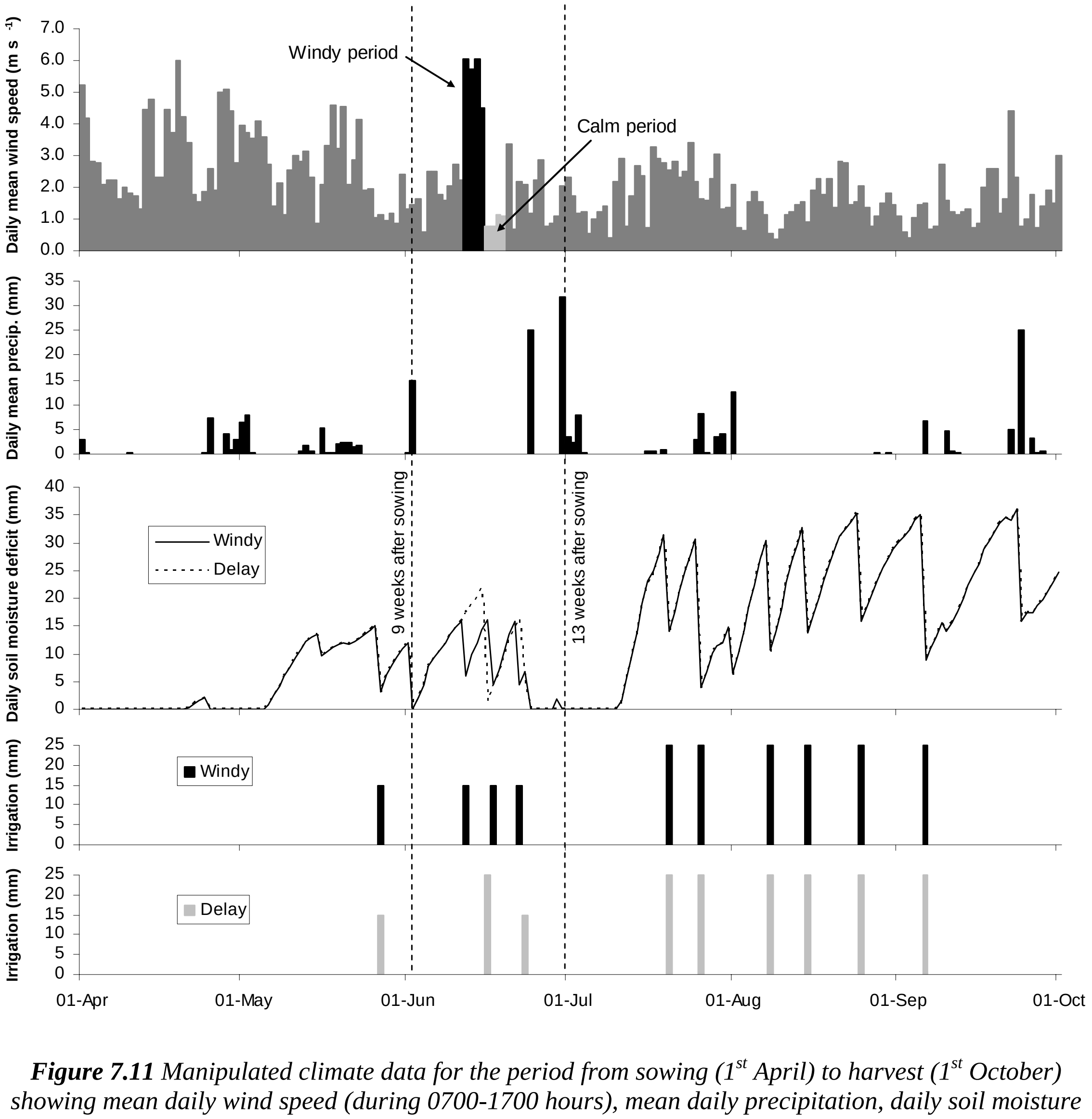

Figure 7.11 *Manipulated climate data for the period from sowing (1st April) to harvest (1st October) showing mean daily wind speed (during 0700-1700 hours), mean daily precipitation, daily soil moisture deficit (for both windy and delay scenarios) and irrigation applications (for both windy and delay scenarios).*

Irrigation applications for both scenarios were simulated using the TRAVGUN-TRAVELLER model assuming that all irrigations were carried out during the day (starting at 0700 hours) with the travel lanes orientated at 90° to the prevailing wind using a 70 m lane spacing and a 210° sector angle. The Carrot Calculator and carrot quality models were then used to evaluate the impacts on crop yield and quality of each scenario. The results from the simulation are presented in Table 7.9.

Table 7.9 *Impact of two irrigation management scenarios (windy and delay) on application uniformity and total, marketable and premium root yield.*

Output		**Windy scenario**	**Delay scenario**
Uniformity of affected irrigation event	**CU**	67.8	92.0
	DU	41.6	88.3
Seasonal uniformity	**CU**	94.7	95.3
	DU	92.0	93.1
Total yield (t ha^{-1})		**133.8**	**133.4**
Marketable yield (t ha^{-1})		**99.4**	**97.3**
Premium root yield (t ha^{-1})		**64.7**	**62.1**

It can be observed from these results that, although irrigating during the windy period considerably reduced the application uniformity of the individual event compared to delaying irrigation for four days until calmer weather, the seasonal application uniformity was almost identical for both scenarios. However, by delaying irrigation rather than irrigating during the windy period, total, marketable and premium root carrot yields were reduced by 0.3%, 2.1% and 3.9% respectively.

Application of the integrated model to these scenarios therefore indicated that growers should maintain irrigation schedules even in the event of high winds since the crop losses which resulted from delaying irrigation until calmer conditions were greater than those which occurred as a result of non-uniform irrigation caused by high winds. However, it should be noted that this example was configured to place the timing of the windy/delay scenario during a critical crop growth stage for water requirements. Furthermore, the example was carried out using climate data for a dry year in which an additional dry period was artificially created during this critical crop growth stage. Therefore, at other crop growth stages, or in other seasons of differing irrigation requirements, the outcomes of such a scenario may vary, or indeed be reversed.

It can therefore be seen that the integrated modelling approach developed in this thesis provides a useful tool to evaluate and quantify the impacts on application uniformity and crop production not only of equipment and management strategies relating to raingun operation, but also the impacts of day-to-day management decisions (such as whether to irrigate in windy conditions or what irrigation schedule to use). In addition, the approach could be used to estimate the potential crop losses due to seasonal water restrictions to assist growers in their defence of the restrictions or in any resultant compensation claims.

7.5.2. Impact of climate change

The integrated modelling approach could also be used to evaluate and quantify the impacts of climate change on crop production under raingun irrigation. As an example of this application, the approach was used to examine the impact of predicted changes in wind speed on raingun application uniformity and carrot crop yield and quality.

Climate change predictions for use in this example were obtained from the UKCIP02 database (UKCIP, 2006). This database was created as part of the UK Climate Impact Programme (UKCIP). It provides meteorological data for the UK either on a 50 km or 5 km grid for the baseline period of 1961-1990 and the projected changes in these variables at various future time-slices (2020s, 2050s and 2080s) according to four potential greenhouse gas emission scenarios – low, medium-low, medium-high and high (Hulme *et al.*, 2002). The projected changes in wind speed[9] and the impact of this on raingun application uniformity and crop production were examined for one of these scenarios; medium-high emissions for the time-slice 2050s.

Baseline mean daily wind speed data and the projected changes from this were obtained for the 50 km grid relating to site I2003 (grid 376) from the UKCIP02 database and were compared to site I2003 (Table 7.10). Typically in climate change evaluations, the baseline data is compared to observed data, and, assuming that the two data-sets were similar, the observed data is then perturbed by the projected changes from the baseline to gain a future climate data-set for the scenario to be studied. However, in this case, no direct comparison of the baseline data to I2003 could be made due to the differences in

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[9] Note that no data is available on projected changes in wind direction.

height of the measurements. Therefore, for the purposes of this example, an assumption was made that applying this perturbation to the observed I2003 data was valid. It is immediately apparent from Table 7.10 that the projected changes in wind speed at this location for the selected scenario are relatively small, particularly during the summer period when irrigation might be required (late May to late September).

Table 7.10 *Mean daily wind speed at site I2003 and the baseline and projected change data for the relevant area based on the medium-high emissions scenario for the time-slice 2050s.*

Dataset	**Mean daily wind speed (ms^{-1}) during:**											
	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
I2003 (2 m height)	2.6	2.1	2.0	2.3	2.0	1.4	1.4	1.1	0.9	2.0	2.2	2.1
UKCIP02 baseline (10 m height)	6.8	6.6	6.0	5.5	5.2	4.9	4.8	5.0	5.3	5.7	6.1	6.6
UKCIP02 medium high scenario (2050s) Anomaly from baseline (%)	3.2	3.0	2.0	0.9	0.4	0.4	-0.2	-1.4	-2.2	-1.7	0.2	2.2

The perturbed I2003 data was then used in the TRAVGUN-TRAVELLER model to simulate irrigation applications for the site, assuming an identical irrigation schedule as for non-perturbed data (since no other climate variables were altered) and day-time irrigation at 90° to the prevailing wind direction using a lane spacing of 70 m and a sector angle of 210°. These simulated applications were then compared to the relevant irrigations using the non-perturbed data-set.

The irrigation applications simulated under this future scenario were identical to those using the observed I2003 data. Indeed, the perturbed wind speed data itself was identical to the non-perturbed data. This was due to the very small proportional changes in wind speed projected by the medium-high emissions scenario for the 2050s and the resolution of the wind data requirements for modelling (0.1 ms^{-1}). Consequently, it was not necessary to continue the simulation using the crop modelling component of the integrated approach. It was noted that, even under the most extreme climate change scenario (high emissions in time-slice 2080s), the maximum projected anomaly in wind speed during the irrigation season (May to September) was -5.1%. It is therefore reasonable to conclude that climate change is likely to have little impact on wind speed and therefore on irrigation uniformity in the foreseeable future.

By following the process used on wind speed data in this example for other climate variables (e.g. temperature, relative humidity, global radiation and precipitation), the integrated modelling approach could readily be used to investigate the impacts of future climate change on irrigated crop production. For example, it could be used to assess the likely changes in irrigation requirements due to changes in precipitation and evapotranspiration rates, or to evaluate the potential changes in crop growth rate due to changes in temperature and radiation inputs. However, such evaluations lie outwith the scope of this study.

7.6. Summary

The integrated modelling approach developed in this thesis was used to simulate the impacts of a range of raingun equipment and management strategies on irrigation uniformity and the subsequent impacts on crop production in two stages. The first stage used the TRAVGUN-TRAVELLER raingun model to simulate the spatial heterogeneity of irrigation application for a range of equipment and management scenarios (field orientation, lane spacing, sector angle and night/day irrigation). The second stage used the outputs from the raingun model as inputs to the Carrot Calculator and crop quality models to assess the impacts of non-uniform irrigation on carrot crop yield and quality.

The primary findings from raingun modelling were:

i) Measures of system performance using overall seasonal application uniformity may underestimate the impact of non-uniformity on crop production due to the masking of random variations in non-uniformity during specific irrigation events;

ii) Measures of irrigation uniformity using catchcan transects are sensitive to both the location of transects within the field and the timing of measurements as a result of short-term variations in wind conditions. Consequently, system evaluations using a single transect should be interpreted with care;

iii) Field orientation to the prevailing wind direction had a relatively limited impact on application uniformity, although its significance increased at lane spacings wider than 70 m. Where possible, fields/travel lanes should therefore be orientated perpendicularly to the prevailing wind direction to minimise non-uniformity;

iv) Lane spacing had a considerable impact on application uniformity. Maximum uniformity was obtained with a lane spacing of 70 m where wind speeds were <2 m s^{-1}. At higher wind speeds, there were indications that lane spacing should be reduced to 60 m, but only where a suitable sector angle was selected. This indicated that the industry recommended spacing of 72 m may therefore be marginally too wide, particularly under windy conditions;

v) Sector angle had a considerable impact on application uniformity. Maximum uniformity was obtained with a sector angle of 180° when using a 60 m lane spacing and 210° at 70 m spacing. At higher wind speeds there were indications that increasing the sector angle by 30° may be beneficial, and;

vi) Mean wind speed during irrigations had a considerable effect on application uniformity. Gentle winds tended to slightly increase uniformity, but higher wind speeds caused a rapid decline in uniformity, particularly at wider lane spacings. This supports industry advice to irrigate at night where possible, when wind speeds are typically lower.

The primary findings from the crop modelling were:

i) Achieving high irrigation uniformity is an important factor for carrot crop production, particularly in years of high irrigation demand;

ii) Irrigation uniformity not only impacts on carrot yield, but also on crop quality. For example in a year of relatively high irrigation demand, low application uniformity throughout the entire season resulted in reductions of up to 4% in total yield, 8% in marketable yield and 11% in premium root yield;

iii) Even a single low uniformity irrigation event during critical crop growth periods can have a small but appreciable impact on carrot crop yield and quality.

In addition to evaluating the impact of equipment and management strategies on raingun irrigation uniformity and the consequent impacts of this for crop yield and quality, the integrated modelling approach has been demonstrated to have other applications. Two examples have been provided which show how the approach can be used to evaluate the impact of day-to-day irrigation management decisions and to investigate the potential impacts of future climate change on application uniformity and crop production.

The first example demonstrated an advantage to irrigating despite strong winds over delaying irrigation until calmer conditions. Total, marketable and premium root yields were reduced by 0.3%, 2.1% and 3.9% respectively by delaying irrigation by four days until calmer wind conditions when the windy/delay choice fell during the critical crop growth period of 9-13 weeks after sowing in a dry year. However, the effect of such decisions may be different at other times during the growing season or in years with different irrigation needs.

The second example demonstrated that the changes in wind speed at site I2003 projected by the UKCIP02 medium-high emissions scenario for the 2050s would have no effect on irrigation uniformity and crop production. It is likely that, even in the most extreme climate change scenario, wind speeds (and consequently irrigation uniformity) would be little affected.

The integrated modelling approach could be used to further investigate other irrigation management decisions such as the impacts of changing the irrigation schedule or to estimate the potential crop losses due to seasonal water restrictions. In addition, the approach could be used to fully investigate the potential impacts of future climate change on irrigated crop production in the UK. However, such investigations lie beyond the scope of this research.

A critical evaluation of the integrated modelling approach developed in this thesis and the implications of these findings are discussed in detail in the following chapter.

8. Discussion

This chapter evaluates the sensitivities of the modelling processes used in the research, discusses the implications of the research findings, develops recommendations for growers, and suggests options for future research. Firstly, the sensitivities, advantages and limitations of the integrated modelling approach and the component models are evaluated. The implications of the research findings for crop production, for assessing and demonstrating efficient irrigation water use and for the irrigated agriculture industry in general are then discussed. Recommendations for growers to assist them to improve the efficiency of raingun irrigation are then presented. Finally, suggestions for relevant future research are proposed.

8.1. Advantages and limitations of modelling process

The advantages and limitations of the integrated modelling approach and its constituent components are discussed below.

8.1.1. Integrated modelling approach

The integrated modelling approach developed in this thesis inevitably has a number of limitations. Firstly, it is recognised that the approach was relatively restricted in its application to a single irrigation system (rainguns) used on a single crop (maincrop carrot variety Nairobi) under standard crop husbandry practices. There are, of course, other irrigation systems, crops and husbandry practices which have not been considered. However, the integrated approach is readily transferable to other overhead irrigation systems and crop types. Secondly, the use of existing models resulted in some data incompatibility issues. Computer programs were required in order to manipulate the various datasets into suitable formats for further simulation and evaluation. Thirdly, as with any linked modelling processes, any errors generated in early phases of the modelling (e.g. slightly unrealistic distortion of irrigation application due to wind conditions) are likely to be propagated in subsequent modelling processes. The extent and impact of modelling propagation error is unknown.

However, research such as this requires an holistic approach in order to understand and simulate the complex crop responses to non-uniform irrigation as a result of the raingun equipment and management strategies employed. Such an approach could only be provided by the integrated modelling process developed in this thesis; it would have been impractical to address the issues of this research using only experimental methods. Furthermore, the integrated approach had the advantage of coupling existing models to simulate raingun irrigation and crop growth. This reduced the requirement to develop new models, and has importantly provided a number of practical applications for previous research. Therefore, despite some limitations, the integrated modelling approach developed and used in this thesis provided a practical, coherent and robust method to achieve the research aim.

8.1.2. Modelling water distribution from rainguns

The raingun irrigation simulation model used in this research comprised two components – the wetted pattern generator (TRAVGUN) and the field application model (TRAVELLER). The advantages and limitations of these respective components are discussed separately below.

TRAVGUN model

The wind affected wetted patterns generated using TRAVGUN were highly dependant on the transects used for model calibration, primarily as a result of the algorithms used to convert transect data into a wetted pattern for subsequent model calculations. Consequently, a calibration dataset which resulted in wind affected wetted patterns with a good fit to observed data was only found with extensive testing. However, even with a good statistical fit to observed data the model tended to simulate particularly high application rates near the maximum throw range at low wind speeds and exhibited slightly limited range shortening perpendicular to the wind direction and elongation down wind at wind speeds of >2.5 m s^{-1}. In addition, the maximum wind speed simulated by TRAVGUN was 5.5 m s^{-1} (compared to observed wind speeds of up to 11.4 m s^{-1}). As a result, confidence in model performance was highest for moderate wind speeds of between about 1.5 m s^{-1} and 3 m s^{-1}, but was reduced for both higher and lower wind speeds. These limitations may have contributed to a slightly lower sensitivity to wind conditions in the field level simulator than may occur in reality.

However, TRAVGUN had a number of advantages for use in this research. The model uses algorithms derived from the established raingun models of Richards and Weatherhead (1993) and Al-Naeem (1993) which were developed for typical raingun systems used in the UK. Model calibration for a particular raingun configuration (using three transects collected under still and windy conditions) was relatively straightforward compared to the large data requirements of other raingun models (e.g. Richards and Weatherhead, 1993; Al-Naeem, 1993; Grose, 1999). Once calibrated, the model's simple and accessible Windows™ interface allowed efficient generation of wind-affected wetted patterns under a range of wind speeds and any wind direction for any required sector angle. These wetted patterns were produced as an array with 1 m spacing, from which the appropriate data points for any field level grid spacing could then be selected.

TRAVELLER model

TRAVELLER used a database of wind affected wetted patterns generated by the TRAVGUN model to simulate field level irrigation application according to wind conditions and equipment set-up. Consequently, the performance of TRAVELLER was dependant on the quality of these wind affected wetted patterns (see above). TRAVELLER did not simulate raingun progress down the field as a continuous movement, but rather as a series of discrete steps at 5 m intervals with the period of time that the gun applies wetted patterns at any one point determined by the defined travel speed. This may have affected the estimated application depths compared to an alternative approach of simulating continuous raingun movement. In addition, the wind data which the model used to select the appropriate wetted pattern to apply in a given location was based on the prevailing conditions during a 15 minute interval. The effect of gusting wind conditions on application uniformity may therefore not have been fully simulated by TRAVELLER.

The primary advantage of the TRAVELLER field level irrigation model was that it allowed simulation of a very large number of irrigation events using a range of raingun equipment and management strategies in a relatively small processing time (8,704 simulations required approximately 18 hours on a standard Pentium 4™ computer). Options available for simulation (provided that the appropriate wind affected wetted patterns have been generated using TRAVGUN) included: raingun make, model and nozzle type; water pressure; trajectory angle; sector angle; field orientation relative to prevailing wind; pull speed; pull start times and lane spacing. If a smaller discontinuous movement of the raingun than 5 m were simulated (or indeed a continuous movement), the increased number of iterations and interpolation required to calculate applied water depths would result in a prohibitively long processing time. Although the use of 15 minute interval wind data may have limited the impact of gusting wind conditions on irrigation application, it is rare to obtain wind data with a finer time-step. In addition, research by Al-Naeem (1993) indicated that there was little difference in application uniformity between raingun simulation using wind data with up to one hour time intervals. Therefore, both restricting raingun movement to 5 m discrete steps and the use of 15 minute interval wind data were considered valid limitations to the simulation process.

Despite its limitations, the TRAVGUN-TRAVELLER raingun irrigation model performed acceptably compared to observed irrigation applications over a number of irrigation events. The model therefore provided a useful tool to examine the effects of changing a number of equipment and management strategies on raingun uniformity. Such evaluation could not be performed by experimentation alone.

8.1.3. Modelling crop yield and quality response to irrigation

The advantages and limitations of the carrot crop yield model (the Carrot Calculator) and the carrot quality model used in this research are discussed separately below.

The Carrot Calculator

The Carrot Calculator model was used to simulate crop yield response as a result of non-uniform irrigation during a season. The primary limitation of the model was that the deleterious effects of excess irrigation on crop growth were not simulated – only sub-optimal irrigation was taken into account. Consequently, irrigation strategies that resulted in excessive application depths and low application uniformities (e.g. those with narrow lane spacing) tended to result in crop yields which were not dissimilar to those obtained under high application uniformity. In reality, crop growth may have suffered due to over-irrigation. A further limitation of the model was that it was not possible to calibrate for the carrot variety (or type) typically used in UK production: instead, existing calibrations for processing carrot varieties were used. These varieties may have differed slightly in their growth characteristics and response to water shortages from the Nairobi variety used in this research. Finally, a considerable amount of agroclimatic and crop growth data were collected for the parameterisation and validation of the STICS model. However, due to the rejection of this model in favour of the Carrot Calculator model, there was limited soil chemistry data available for the parameterisation and validation of the latter. Consequently, it was necessary to assume that the crop was not limited by soil nutrient status for all simulations. As a result, the performance of the Carrot Calculator could only be validated following the application of a correction factor.

The Carrot Calculator had a number of advantages for this research – foremost among these was its simple and accessible Windows™ graphical user interface which facilitated simulation of crop yield at up to 2047 grid points in batch processing mode. This allowed evaluation of the spatial variability in carrot yield using irrigation application data at each grid point (derived from the spatial data generated by the raingun model) for a number of irrigation scenario/climate year combinations. Furthermore, the Carrot Calculator output could be generated on any given day after sowing and provided estimates of potential and actual crop evapotranspiration which were used as an indicator of crop stress in the quality model. An additional advantage of using the Carrot Calculator model is that it has been partially calibrated for a range of other vegetable crops such as beans and lettuce (although these models were not available for this research). This may allow future research to evaluate the impacts of restricted or non-uniform irrigation on the production of a range of other vegetable crops.

Despite its limitations, the Carrot Calculator performed well in predicting crop yields compared to observed data under a range of experimental irrigation deficit treatments. It was therefore concluded that the Carrot Calculator constituted a useful tool to enable realistic simulation of carrot crop yield response to non-uniform irrigation.

Carrot quality model

The carrot quality model uses estimated potential and actual crop evapotranspiration during critical crop growth stages along with total yield data generated by the Carrot Calculator to predict marketable yield based on three key root quality criteria (establishment and uniformity, scab and root morphology). The impact of water shortages on the three quality factors was estimated using feedback from key informants in the carrot industry. However, since the quality model relied on outputs from the Carrot Calculator, no estimate could be made of the deleterious effects of excess irrigation on root quality. In addition, there are particular sensitivities in the calculation of quality losses due to scab infection. Carrot scab was only assumed to infect roots after the point at which water shortages caused plant stress. However, it is likely that scab may infect the crop once soil water conditions are sufficiently dry for disease mobilisation, but before water shortages are sufficient to cause plant stress. Consequently, the simulated quality losses due to scab infection may not be accurate. Because different carrot varieties, soil types, husbandry practices and locations differ in the root quality issues they present, the model was necessarily limited to variety Nairobi grown on loamy sand using industry standard methods. It was also necessary to assume that pesticide and soil nutrient management were optimal and that the effect on quality of other disease and physiological disorders was not related to the irrigation regime. In reality, many root quality issues other than the three identified factors are related to the irrigation regime (both under- and over-irrigation). The model is therefore somewhat limited in its application and presents only a limited assessment of the potential impacts of non-uniform irrigation on crop quality.

However, for the purposes of this research, the development of a model to predict carrot root quality response to irrigation was essential since none previously existed. The spreadsheet model developed was necessarily simple and limited due to the complexity of the subject. Nevertheless, the model covered the three key factors affecting root quality (identified by industry experts) for a typical crop under standard husbandry practices.

Despite its limitations, predictions of marketable yields using the Carrot Calculator and the carrot quality model at site R2004 proved adequate. However, estimations of premium root yields were poorer. It was therefore concluded that although the combined carrot yield and quality model is somewhat limited in its application, it provides a useful and much needed tool for predicting the impact of irrigation non-uniformity on crop production. The approach used in the carrot quality model could be further developed to include other disease and physiological root quality issues in order to increase understanding of the impacts of crop husbandry practices on root quality.

8.2. Implications for crop production

This thesis has demonstrated two major findings which relate to crop production:

i) Low irrigation uniformity results in reduced carrot crop yield and particularly quality. This can result from even a single low uniformity irrigation event during the growing season, and;

ii) Low irrigation uniformity from hose-reel raingun systems can be ameliorated by paying close attention expected wind conditions during irrigation and modifying equipment and management strategies accordingly.

An economic evaluation of the financial impacts of changing raingun equipment and management strategies on crop production and net profit is beyond the scope of this study. However, as an indication of the potential financial implications of irrigation practice, the impact of crop yield and quality losses attributed to raingun irrigation non-uniformity on income are discussed below.

There are a number of ways in which growers are typically paid for their carrot crop – these vary according to the target market for which the crop is grown (e.g. fresh or processing) and the contracts of individual packers/processors. Two of the most common contracts are:

i) a payment per tonne of dirty roots ex-farm (i.e. harvested total yield) provided that certain quality criteria are met, and;

ii) a payment per tonne of marketable roots ex-farm (usually determined by field or factory samples as a percentage of the total harvested dirty roots) (Will, *pers. comm.* 2006; Wright, *pers. comm.* 2006).

Prices per tonne for both these types of contract vary according to the market demand at the time of harvest, the level of grower input in crop production, the type of crop (e.g. early/maincrop/stored and fresh/speciality/processing) and the grading structure used by packers/processors (which depends on the final end market). Typical prices paid for a crop are difficult to specify owing to this range of influencing factors. However, industry advice suggested that a current average price for a maincrop of variety Nairobi, produced entirely by a grower, harvested at the beginning of October and destined for the fresh market might typically be £50 t^{-1} for contract type (i) and £75 t^{-1} for contract type (ii).

Consider the examples given in Sections 7.4.4 and 7.4.5 for a crop grown during a relatively dry year (I2003). Simulations of crop growth during this year indicated that under high irrigation uniformity through the season, total root yields were 134 t ha^{-1} (equating to a dirty root yield of 144 t ha^{-1} assuming a soil content of 7%) and marketable yields were 100 t ha^{-1}. Using the above figures, this might realise an income of around £7,200 ha^{-1} under contract type (i) and around £7,500 ha^{-1} under contract type (ii). However, if irrigation uniformity was low throughout the entire season, total and marketable crop yield losses (from the yields attained under high application uniformity) were estimated to be 4.0% and 7.8% respectively. This equates to an income loss of around £288 ha^{-1} under contract type (i) and £585 ha^{-1} under contract type (ii). Further simulations indicated that total crop yield and marketable yield losses of about 0.3% and 0.9% respectively may result from a single low uniformity irrigation event during critical crop growth stages. These losses would equate to an income loss of approximately £25 ha^{-1} under contract type (i) and £68 ha^{-1} under contract type (ii).

Given the narrow profit margins of producing a commodity vegetable such as carrots, these income reductions are likely to be significant to growers. Therefore, ensuring the highest possible application uniformity during all irrigation events should be regarded by growers as a critical component of their farming operations. This can be achived in part by paying close attention to the expected wind conditions during irrigation, and modifying the equipment and management strategies accordingly. The findings from this research indicate that lane spacing and sector angle are of particular importance in attaining high irrigation uniformity. However, other variables not considered in this research, such as trajectory angle and particularly water pressure are also important in achieving high uniformity, so should also be carefully considered and monitored.

Achieving a high irrigation uniformity will not only benefit profit margins by ensuring optimal crop production, but will also have implications for growers in terms of demonstrating the efficient use of water for contractual obligations within grower protocols and for abstraction licence renewal.

8.3. Implications for demonstrating efficient irrigation

Growers are under increasing pressure to demonstrate that they irrigating efficiently both to meet the requirements of grower protocols and as part of the new abstraction licence renewal process. For example, article 7.2.1 in the Generic Crop Protocol of the Assured Produce Scheme (for horticultural crops) states that "The most efficient and commercially practical water delivery system should always be used…" (Assured Produce, 2005). Furthermore, recent changes in legislation now require growers to demonstrate efficient use of water (defined as "the right amount of water in the right place at the right time") as part of abstraction licence renewal (EA, 2005).

However, there is currently no agreed method either for growers to demonstrate efficient irrigation or for the protocol regulators or the Environment Agency (EA) to assess irrigation efficiency. In response to this uncertainty, Knox (2005) proposed "a pathway to efficiency" to assist growers and/or the EA to assess on-farm irrigation water management practices in the context of licence renewal (Figure 8.1). Although this pathway was designed within the context of licence renewal, the processes relate equally to irrigation efficiency in the context of grower protocols. The "pathway to efficiency" is discussed in more detail below.

The first element – "understanding your system" – is the critical starting point of the pathway to efficiency. Using carefully chosen subjective questions, grower understanding of their irrigation operations relating to water resources management and equipment can be assessed, allowing identification of areas where improvements can be made. "Optimising the irrigation network and equipment" focuses on three key areas – pressure, water use and application uniformity. Growers need to perform regular checks on water pressure and the volumes distributed within their conveyance systems to ensure that these match pump and equipment capacities. In addition, the performance of irrigation equipment and the strategies used in their operation should be checked using in-field catchcan evaluation of application uniformity. “Optimising soil and water management practices” refers to using an appropriate method of irrigation scheduling to ensure that irrigation applications are matched to crop needs without over-application. Collectively, these steps lead to demonstrating “best practice” in irrigation. This final stage also includes issues such as rating irrigation highly in the farm management system, understanding the soil from an irrigation perspective, designing and maintaining irrigation systems correctly, monitoring all aspects of irrigation events and keeping abreast of new developments in irrigation science.

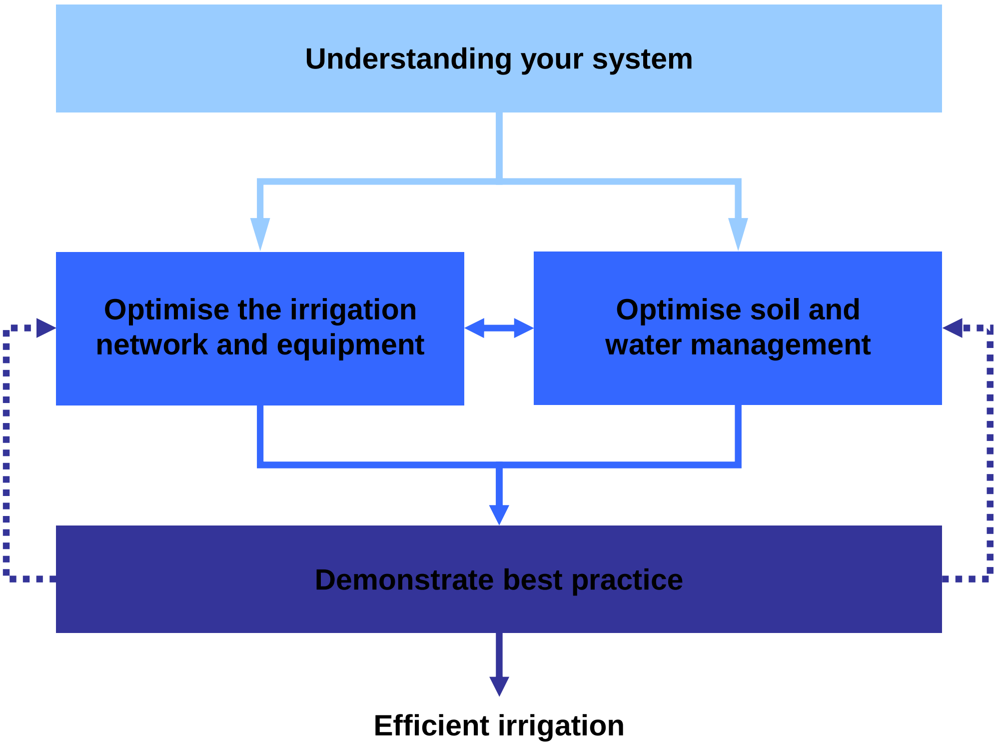

Figure 8.1 *Schematic representation of the pathway to efficiency (Knox, 2005)*

The integrated modelling approach developed for this study and the research findings themselves will provide an important role in the proposed “pathway to efficiency” by:

i) Highlighting the importance of using the appropriate raingun equipment and management strategies to achieve more uniform irrigation applications;

ii) Demonstrating the potential impact on crop production of low irrigation uniformity, even during a single irrigation event;

iii) Improving the understanding of carrot response to irrigation which may assist in further developing suitable irrigation schedules for the crop;

iv) Providing a useful framework (with further development) to allow investigation of the impact of other raingun equipment and management strategies (or indeed, alternative irrigation systems) on application uniformity and the consequences for crop production, and;

v) Developing guidelines for best practice raingun irrigation relating to the studied equipment and management strategies (Section 8.5).

This research will therefore be of considerable relevance to both growers and regulatory authorities in the context of demonstrating efficient irrigation for meeting grower protocol requirements and for abstraction licence renewal. The findings will help growers understand the implications of non-uniform irrigation on crop production and will assist them to take appropriate steps to improve irrigation efficiency. The research will also inform the protocol regulators and the EA on the complexity of irrigation management and the difficulties in assessing “efficient use of water” for growers who irrigate using hose-reel raingun systems. Further investigations using the integrated modelling approach of this thesis could also provide valuable information relating to other key factors which affect raingun performance and/or crop production – notably water pressure, trajectory angle, day-to-day management decisions, the importance of irrigation scheduling and the potential impacts of future climate change. In addition, the approach could also be used to evaluate the impacts of alternative overhead irrigation systems on a broad range of irrigated crops.

8.4. Other implications for the irrigated agriculture industry

The findings of this research have further implications for the irrigated agriculture industry, primarily relating to other crops, alternative overhead irrigation systems and to irrigation equipment manufacturers. These areas are discussed below.

8.4.1. Implications for other irrigated crops

Although this research was confined to a single crop type (carrots) grown under typical production conditions for the UK, many of the findings can be readily transferred to other irrigated crops. In particular, other root crops with a similar physiology (e.g. parsnips and perhaps also beetroot and sugar beet) are likely to respond to irrigation non-uniformity from rainguns in a similar manner to carrots. It is therefore likely that yield and quality losses for these crops due to low application uniformity may be of a similar magnitude to those found for carrots. Other irrigated crops such as brassicas, salad crops and potatoes will respond to application non-uniformity from raingun irrigation in a different way, depending on their relative sensitivity to irrigation for yield and quality. However, in principle, these crops are also likely to show reductions in yield and quality due to low application uniformity. The integrated modelling approach used in this thesis could therefore be modified to include alternative crop specific models – using for example the Lettuce Calculator developed by Reid (2005c), the SIMPOTATO model for potatoes (Hodges, 1998) or some of the grain legume, cereal or vegetable crop models within the DSSAT suite (Jones *et al.*, 2003; ICASA, 2006). This would allow more accurate estimation of the impacts of non-uniform overhead irrigation across a broad range of crops.

8.4.2. Implications for alternative overhead irrigation systems

The implications of application uniformity for crop production highlighted in this research have relevance for alternative overhead irrigation systems other than hose-reel rainguns – for example centre pivots, linear moves or sprinklers. A simple appraisal of crop response to alternative irrigation systems could be obtained using measurements of seasonal application uniformity to estimate carrot total, marketable and premium root yield using Figure 7.9. However, a more accurate assessment could be obtained by modifying the integrated modelling approach to include suitable alternative irrigation application models. The use of simple data-bridging techniques to link irrigation and crop growth models readily allows replacement of the TRAVGUN-TRAVELLER raingun model with an alternative – e.g. the centre pivot model developed by le Gat and Molle (2000) and Molle and le Gat (2000) or the SIRIAS sprinkler model (Carrion *et al.*, 2001; Montero *et al.*, 2001).

With further development, the integrated modelling approach could therefore form part of a package which irrigation specialists, agronomists or growers could use to evaluate irrigation systems and their impact on a wide range of crop types. This may assist growers in considering the potential benefits of changing to an alternative irrigation system or cropping rotation in order to adapt to future water resource constraints.

8.4.3. Implications for irrigation equipment manufacturers

Although this research only examined the impacts of changing a relatively small number of raingun strategies, it has highlighted the importance of these factors in attaining high irrigation uniformity. However, it is apparent that raingun manufacturers are generally unaware of the impacts of in-field equipment set-up and operation on application uniformity. The majority of manufacturers only supply literature to customers which identifies flow rates under different water supply pressures and the resulting throw range under still wind conditions. Few provide advice on the lane spacing required to counter higher wind conditions and none appear to give guidance on the impacts of other equipment settings (e.g. sector angle, trajectory angle, rotation speed, nozzle type etc.).

The modelling approach developed in this study could provide significant new information for suppliers to support the development of more comprehensive user manuals for their equipment. For example, by using the TRAVGUN-TRAVELLER model, equipment manufacturers could readily evaluate the impacts on application uniformity of a wide variety of equipment settings under a range of wind conditions. The benefits of this would be two-fold: firstly such evaluation would help to identify aspects of raingun design which are key to application uniformity under windy conditions; and secondly, this would allow more explicit guidance for users of the equipment to be produced. The information derived would assist irrigators to attain the optimal performance from their systems under variable wind conditions.

A further implication of this research for raingun equipment manufacturers relates to automated raingun setting control systems. It was apparent from the results in Figure 7.5 and Figure 7.6 that no single irrigation strategy suited all wind conditions – rather, sector angle and lane spacing should be adapted according to the ambient wind conditions. This re-introduces the concept originally examined by Turker (1998) who attempted to automate sector and trajectory angle control in response to the ambient wind conditions. With the recent technological advances of remote sector angle control and variable trajectory angles on some raingun models, combined with the decreasing costs of automatic weather stations and communications equipment, the development of real-time control systems for rainguns are now worthy of further investigation by equipment manufacturers.

8.5. Developing recommendations for growers

Based on the findings of this research, recommendations to assist growers to improve their raingun irrigation uniformity have been developed. These guidelines cover three main areas: (i) recognising the importance of irrigation uniformity; (ii) measuring system performance and (iii) achieving high irrigation uniformity. These three topics are presented below.

8.5.1. Recognising the importance of irrigation uniformity

Ensuring high irrigation uniformity is important, not only for maximising crop yield and, in particular, quality but also in order to demonstrate efficient water use for abstraction licence renewal and grower protocols. Based on the findings of this research, growers should aim to achieve a seasonal uniformity with a CU and DU of >85% for optimal crop production.

However, while the common perception of growers that non-uniformity during single irrigation events will ultimately even out over a season in terms of seasonal application depth (mm) is valid, it does not account for the appreciable impact that a single low uniformity irrigation event can have on crop yield and quality. Consequently, it is important to ensure high uniformity (CU of 80-95% and DU of 70-90%) during individual irrigation events, particularly during critical crop growth stages (typically mid- to late-season with regard to total carrot yield and early- to mid-season for root quality). However, preliminary investigations in this research suggested that there may be yield and quality advantages to irrigating during a windy period (despite causing low uniformity) rather than delaying irrigation until calmer conditions.

8.5.2. Measuring system performance

Growers can assess the performance of their system using simple catchcan transects across a field with cans laid out between the first and last pulls at a spacing of 2 m to

5 m. However, care needs to be taken when interpreting the results, particularly since variations in wind conditions during a pull and from day to day will affect the measurements. Ideally a number of measurements under different wind conditions should be made both across and down the field.

However, in practice, such extensive catchcan measurements may be difficult to achieve owing to the high labour requirements. Instead, the modelling approach of this thesis could be further developed to provide an evaluation tool which irrigation specialists, agronomists or growers could use to examine the performance of a raingun system (or indeed other overhead irrigation system) using recorded wind data and a small number of catchcan transects as inputs. Using this approach would not only allow evaluation of the application uniformity of the system at the field-level under a range of wind conditions, but would also allow evaluation of the impacts that this has on crop production.

8.5.3. Achieving high irrigation uniformity

High irrigation uniformity from hose-reel raingun systems can be achieved by growers under most wind conditions by paying close attention to the following equipment settings and management strategies.

Field orientation

Despite the relatively small impact of prevailing wind on application uniformity observed in this study, it would still be prudent to follow the industry advice that growers should orientate fields/travel lanes at 90° to the prevailing wind direction where possible (e.g. Schull and Dylla, 1976a,b; Growcom, 2004b; NIC, 1999). Such action would be particularly important in areas with relatively high wind speeds and a strong prevailing wind direction, such as in coastal areas.

Lane spacing

Lane spacing has been shown to have a profound effect on application uniformity, particularly at moderate to high wind speeds. For a typical raingun configuration (Nelson Big Gun SR 150® fitted with a 25.4 mm taper nozzle) this research indicated that the industry standard lane spacing (72 m) may be slightly too wide, particularly where wind speeds exceed 2 m s^{-1}. A lane spacing of 70 m under wind speeds of <2 m s^{-1}, reduced (where possible) to 60 m where wind speeds exceed 2 m s^{-1} would give much higher application uniformity. In addition, observations by Augier (1996) and during this study indicated that lane spacings often deviate considerably (by up to 5 m) from the recommended distance through the season. Consequently, much closer attention to lane spacing should be made when moving raingun equipment and consideration should be given to narrowing the spacing (where possible) when high winds are forecast. It should be noted, however, that care should be taken to ensure that the raingun pull speed is adjusted accordingly in the event that lane spacing is changed.

Sector angle

Sector angle also has also been shown to have a considerable effect on application uniformity. For the typical raingun configuration described above, this study indicated that for a lane spacing of 70 m, a sector angle of 210° may provide optimal uniformity under wind speeds of <2 m s^{-1}. At higher wind speeds where lane spacing cannot be reduced, increasing the sector angle to 240° may help to reduce non-uniformity. In situations where lane spacing can be reduced to 60 m in response to wind speeds of >2 m s^{-1}, a sector angle of 180° may provide optimal uniformity (increasing to 210° where wind speeds exceed 3 m s^{-1}). Consequently, irrigators need to pay close attention to sector angle, and consider changing the angle according to forecast wind conditions (perhaps in combination with altering lane spacing). New raingun technology such as Komet’s Vector Control® system which has remote sector angle control may be useful for this purpose.

Day/night irrigation

Night time wind speeds have been shown to be typically as little as half those measured during the day (but can be more variable), resulting in generally improved irrigation uniformity at night. Night time irrigation may also have the additional benefit of reducing evaporative losses during application (Bailey, 1987). Consequently, growers should follow industry and regulatory authority advice to irrigate at night where possible. Many growers already practice night time irrigation in addition to day time irrigation, particularly during peak demand periods in dry years. This allows them to maintain irrigation schedules under the constraints of a limited amount of equipment. However, it would appear that few growers irrigate at night in order to achieve greater application uniformity.

It should be noted, however, that there is anecdotal evidence to suggest that disease pressure may be increased through night time irrigation as a result of longer periods of when the canopy is wet. Therefore, some caution is required if growers wish to move to predominantly night time irrigation.

Water pressure

Previous research has indicated that the water pressure at the raingun was sub-optimal in over three quarters of the systems investigated in the UK (Millar, 2002). This has consequences for application uniformity. Particular attention should be paid to aged pumping and conveyance systems which have subsequently been extended. These systems are typically constrained by the original pump and pipe sizes which were designed for smaller water volumes, but which are subsequently too small for the larger demands placed on them. This can lead to significant reductions in water pressure and consequently low application uniformity. Irrigators therefore need to ensure that pumping and conveyance systems are correctly designed and adequately maintained for the demands placed on them during periods of high use, so that the required pressure for raingun operation is attained.

Trajectory angle

Previous research has indicated that decreasing the trajectory angle under windy conditions may help to maintain high application uniformity. Most raingun systems currently in use have fixed trajectories and so do not allow such adjustment. However, in areas with consistently strong winds, a fixed trajectory raingun with a lower angle than the industry standard 24° may be considered to reduce wind effects on uniformity. Alternatively, new technology such as the Komet Vari-Angle® or the Nelson SRA150 Big Gun® raingun may provide the opportunity to alter trajectory angle according to forecast wind conditions. The approach developed in this thesis could readily be extended to evaluate the impact of trajectory angle on application uniformity in order to provide guidance for irrigators on the most suitable trajectory angle to use for the ambient wind conditions.

8.6. Further research

This research has developed and applied an integrated modelling approach which allows evaluation of the impact of changing raingun equipment and management practices on application uniformity and the consequences for crop production. Some suggested areas for further research are outlined below:

i) The integrated modelling process used in the research could be streamlined and developed into a single package to reduce the level of data manipulation required between component models. Greater applicability of the model could be achieved by the inclusion of irrigation simulation for a range of different systems and crop growth simulation for a range of alternative crops. Such developments could result in a useful tool for growers and the crop services industry to assess the potential benefits of different irrigation systems and their operation on application uniformity and the consequent impacts for crop production.

ii) Although a preliminary assessment of the impact of non-uniform irrigation during specific critical crop growth stages on yield and quality was carried out, further research is required to gain a clearer understanding of this topic.

iii) The carrot root quality model developed for this research should be further refined and expanded. Improvements might include: greater sensitivity of carrot scab response to irrigation and the inclusion of additional quality factors which are dependant on irrigation.

iv) There exists scope to investigate the impact that excessive irrigation as a result of non-uniform application has on crop yield and quality.

v) There is a need to further develop the TRAVGUN raingun simulation model in order to improve the calibration process based on zero wind and windy transects.

vi) There is a need for further research into the development of adjustable sector angle and trajectory angle rainguns which are remotely operated (e.g. using telemetry systems) or which are automated to suit prevailing wind conditions (expanding on the work of Turker, 1998). Such systems may assist irrigators to achieve application uniformities which could rival alternative irrigation systems such as hose-reel booms, linear moves and centre pivots.

vii) Growers may benefit from in-depth economic analysis of the costs and benefits of investing time and effort to change raingun irrigation strategies (or indeed irrigation systems). This could only be carried out using a similar integrated modelling approach to that developed in this thesis where the impact on crop yield and quality of application uniformities which result from such changes can be evaluated.

viii) Further work is required to calibrate the Carrot Calculator crop yield model for the Nantes type carrot typically grown in the UK in order to provide more accurate simulations of the response of a typical UK carrot crop to irrigation non-uniformity.

ix) The impact of other irrigation management decisions on application uniformity and crop production should be investigated using the integrated modelling approach – for example: expanding the simple illustration given on whether to irrigate in windy conditions or delay until calmer; investigating the impacts of changing irrigation schedules, or; estimating the potential crop losses due to seasonal irrigation restrictions.

x) The impact of future climate change on irrigated crop production in the UK should be investigated using the integrated modelling approach in order to provide the industry with an indication of the potential challenges it may face.

9. Conclusions

This thesis has developed and applied an integrated modelling approach to assess and quantify the impacts of raingun irrigation non-uniformity on field-scale vegetable production. The procedures developed have been used to evaluate of a range of raingun equipment and management strategies for improving irrigation efficiency. A summary of the main conclusions, with respect to the five research objectives defined in Section 1.5.2, is presented below.

Objective (i) *To develop an integrated modelling approach which can be used to evaluate the effect of a range of raingun equipment and management strategies on application uniformity and the consequent impacts on crop production.*

This research has developed an integrated modelling approach, linking raingun irrigation and crop yield and quality models, to simulate the effects of a range of equipment and management strategies on irrigation uniformity and the consequent impacts on field vegetable crop production in the UK. Outputs from the modelling process include datasets which can be used to generate detailed field level maps showing the spatial and temporal patterns in application uniformity and the resultant variations in crop yield and quality.

Application of the integrated approach using historical climate data provides a useful insight into the importance of achieving high application uniformity and the implications for crop production, for demonstrating irrigation efficiency (both in the context of meeting grower protocol requirements and for abstraction licence renewal) and for the irrigated agriculture industry in general. The findings from the modelling process can then be used to develop recommendations to assist growers in improving their irrigation management practices.

Objective (ii) *To review and assess the data requirements and suitability of potential raingun and crop models to fit the research framework.*

A critical review of raingun simulation models suitable for this research originally identified the mechanistic model of Grose (1999). However, it was subsequently found that this model was limited in its ability to simulate a suitably wide range of raingun equipment and management strategies. Therefore, a more flexible approach using the semi-empirical raingun model "TRAVGUN" (Newell *et al.*, 2003; 2006) combined with a new field level raingun simulation model "TRAVELLER" (de Vries, 2006) was ultimately chosen. This TRAVGUN-TRAVELLER model operated by selecting the appropriate wind affected wetted pattern for the ambient wind conditions from a database of patterns generated using the TRAVGUN component. These patterns could then be applied and overlapped to simulate raingun pulls down a field according to pre-defined equipment and management strategies (e.g. raingun configuration, field orientation to prevailing wind, travel lane spacing, water pressure, trajectory angle, sector angle, and day versus night irrigation).

Similarly, a critical review of crop growth models suitable for this research originally identified the generic crop growth model "STICS" (Brisson *et al.*, 1998; 2002; 2003). However, concerns over difficulties in calibrating and operating STICS within the integrated modelling process led to its rejection in favour of a newly published mechanistic crop-specific model – the Carrot Calculator (Reid, 2005a,b). By using the spatially variable irrigation application outputs from the TRAVGUN-TRAVELLER model, the Carrot Calculator could be used to simulate the impacts on crop yield of variations in application uniformity caused by changing equipment and management strategies.

No models were identified which were capable of simulating carrot root quality as a result of irrigation/soil water status. Indeed, crop quality in general, despite being crucial to revenue, seems to have been largely overlooked in most crop sectors. This is most likely due to the complexity and interaction of the factors which influence crop quality. Therefore a new, simple spreadsheet model was developed for this research which would enable the impact of non-uniform irrigation during critical carrot growth stages on crop quality to be estimated. The model operated using established principles for defining crop stress due to water shortage during critical growth stages (derived from Carrot Calculator outputs) and relating this to potential quality losses (derived from industry advice) which may occur as a result of crop water stress in these periods.

Objective (iii) *To conduct fieldwork to collect relevant soil, crop and irrigation data for model development and application.*

Relevant field data were collected from two commercial carrot growing sites in East Anglia over two seasons.

Irrigation application depths, soil characteristics and crop growth parameters were recorded at a number of 5 m square plots during the growing season at both field sites. At one site, a number of plots were subjected to limited or zero irrigation through the season using mobile shelters. These experimental plots indicated that restricted irrigation resulted in a trend towards reduced canopy growth and root yields. That a stronger relationship between crop production and droughting was not found was attributed to high rainfall towards the end of the season and lateral movement of water into sheltered plots from the adjacent irrigated areas.

Catchcan transects across both field sites demonstrated a large range in application uniformity both during and between individual irrigation events. This was primarily a consequence of varying wind conditions during irrigation, but also related to equipment issues. These results confirmed that opportunities exist for reducing the non-uniformity of raingun irrigation.

In addition to these data, water pressure and wind conditions at the raingun, wetted pattern catchcan data and historical local climate data were obtained. These data were used to parameterise and validate the raingun irrigation, crop yield and crop quality models.

Objective (iv) *To calibrate, parameterise and validate appropriate raingun and crop models for use within the integrated modelling approach.*

The field data was used to calibrate, parameterise and validate the raingun irrigation and crop growth models.

Calibration and parameterisation of TRAVGUN highlighted the limitations of using a small dataset for model calibration, resulting in the requirement to test a large number of possible calibration inputs before a good statistical fit to observed wetted pattern data was obtained. Although there were some concerns regarding the simulated wetted patterns (particularly the tendency to exhibit high application rates near the maximum throw range at low wind speeds and slightly limited pattern distortion under high wind speeds), simulation of field level irrigation application using the TRAVELLER model with these outputs provided an acceptable fit to observed catchcan transect data. It was therefore concluded that the TRAVGUN-TRAVELLER raingun irrigation model presented a flexible and useful tool to simulate field scale raingun irrigation application as a result of changing a range of equipment and management strategies.

The constituent components of the Carrot Calculator crop yield model have previously been validated for two varieties of processing carrot. However, since recalibration of the model for the Nantes type carrot typically used in the UK was not possible, it was necessary to further validate the model for this research using the existing calibration options. Parameterisation of the Carrot Calculator presented some difficulties primarily relating to limited soil chemistry data collection as a result of changing the intended crop growth model from STICS. However, by assuming a non-limiting nutrient supply and applying a correction factor to the results, the model provided a good representation of crop yield response to a range of droughted conditions when compared to observed data. It was therefore concluded that the Carrot Calculator provided an effective tool to enable simulation of the impact on carrot crop yield of non-uniform irrigation.

The carrot root quality model was parameterised for typical production conditions and tested against observed data. Despite the simplicity of the model and a limited representation of potential crop losses due to carrot scab, the model performed adequately in simulating marketable root yields in these production conditions. However, the model did not perform as well in simulating premium root yields. A survey of industry opinion using key informants indicated that, despite being somewhat limited due to its simplicity, the carrot quality model provided a reasonable estimate of carrot quality response to water stress. It was therefore concluded that although the combined carrot yield and quality model may currently be somewhat limited in its robustness, it provided a useful and much needed tool for predicting the impact of non-uniform irrigation on crop production. This model represents the first attempt to quantify both crop yield quality based on agroclimatic conditions experienced during the growing season. Such an approach may have relevance and could be readily modified for application in other crop sectors.

Objective (v) *To investigate the impacts of a range of equipment and management strategies on raingun non-uniformity and crop yield and quality, and to evaluate the implications for the irrigated agriculture industry.*

Using an integrated modelling approach, the impact of a range of raingun equipment and management strategies on application uniformity and the consequences for crop yield and quality were simulated. The implications of the findings for crop production, for demonstrating efficient irrigation and for the irrigation agriculture industry in general were then evaluated. Based on the new information derived from this process, recommendations for growers to improve their irrigation management were developed.

The findings from the irrigation modelling indicated that the closely linked variables of travel lane spacing and sector angle were particularly important in achieving high application uniformity. Importantly, the study suggested that the industry standard lane spacing of 72 m may be marginally too wide, particularly under windy conditions. The research also confirmed previous work which indicated that orientating fields/travel lanes perpendicular to the prevailing wind direction and irrigating at night when wind speeds are typically lower can help to reduce irrigation non-uniformity. Evaluation of crop modelling results demonstrated that maintaining high application uniformity during the entire growing season was important to achieve high yields and particularly quality. Significantly, the findings indicated that even a single non-uniform irrigation event during critical crop growth stages may result in small but appreciable reductions in crop yield and quality, and hence income.

Two further examples of the application of the integrated modelling approach have also been presented – firstly to evaluate the impact of a management decision to irrigate under high winds rather than delay irrigation until calmer conditions, and secondly to investigate the potential impacts of changes in wind conditions due to climate change. Although these examples were of necessity not in-depth evaluations, they illustrate the potential applicability and usefulness of the approach developed in this thesis. Other suggested applications include: examining the impact of changing irrigation schedules;

estimating the potential crop losses due to seasonal water restrictions, and; investigating the potential impacts of future climate change on irrigated cropping in the UK.

This research has demonstrated that irrigation efficiency using hose-reel raingun systems can potentially be improved through careful consideration of equipment and management strategies. By selecting appropriate field orientation, lane spacing, sector angle and timing of irrigation (day/night) the severity of application non-uniformities typical of these systems can be significantly reduced. This can lead to reduced water consumption to meet a minimum application requirement for crop needs and/or an overall increase in crop production.

These findings will be of considerable benefit to growers not only in achieving the production and quality targets demanded by their markets but also in justifying water use and demonstrating efficient irrigation both to satisfy the demands of grower protocols and to meet the tests required for abstraction licence renewal. Conversely, this research will improve the regulatory authorities' understanding of the importance of irrigation for vegetable production and will assist them in recognising the practical difficulties in improving the efficiency of the predominant irrigation system in the UK (hose-reel rainguns). In addition to these benefits for growers and the regulatory authorities, the approach and findings of the research could also assist hose-reel raingun manufacturers to develop technological solutions to the issue of raingun irrigation non-uniformity.

The limitations of the research have been discussed and a range of measures have been identified and described for improving the existing research approach and for future work in this field.

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Appendix A: Wind speed conversions

Metres per second ($m\ s^{-1}$)	Kilometres per hour ($km\ h^{-1}$)	Miles per hour (mph)
0.5	1.8	1.1
1	3.6	2.2
2	7.2	4.5
3	10.8	6.7
4	14.4	8.9
5	18.0	11.2
6	21.6	13.4
7	25.2	15.7
8	28.8	17.9
9	32.4	20.1
10	36.0	22.4
11	39.6	24.6
12	43.2	26.8
13	46.8	29.1
14	50.4	31.3
15	54.0	33.6

Appendix B: Traveller v2.0.5 and data-bridging programs (CD)

Appendix B comprises three folders in the attached CD:

"TRAVGUN to TRAVELLER transformer".

This folder contains the data bridging program used to convert wetted pattern outputs from TRAVGUN (at 1 m grid spacing) to the appropriate format for TRAVELLER (5 m spacing).

"TRAVELLER".

This folder contains the installation files for the program TRAVELLER v2.0.5, including databases of wetted patterns generated using the TRAVGUN model, a selection of weather (wind condition) files and a lookup text file for TRAVELLER operation.

"TRAVGUN-TRAVELLER to Carrot Calculator and CU-DU calculation".

This folder contains the data bridging program used to convert TRAVGUN-TRAVELLER field-level outputs to the appropriate irrigation file format for the Carrot Calculator model. The program also calculates Christiansen's Coefficient of Uniformity (CU) and the Distribution Uniformity (DU) for all TRAVGUN-TRAVELLER outputs.