Overcoming soil water constraints to chickpea yield in rainfed environments of Western Australia and Bangladesh

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Declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary institution.

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Abstract

Chickpea (*Cicer arietinum* L.) is a major cool-season grain legume mainly grown in subtropical environments with summer-dominant rainfall or temperate environments with winter-dominant rainfall. In these environments, represented by the High Barind Tract of Bangladesh (HBT) and south-west Western Australia (WA), respectively, chickpea relies on either stored residual soil water or within-season rainfall. Limited soil water can constrain chickpea growth in both environments, from establishment to pod-fill. This thesis examines agronomic means of alleviating these stresses. It particularly considers the effects of newly introduced mechanised row-sowing and minimum tillage techniques in the HBT on soil water relations.

Plant population density (PPD) (modified through row spacing) and soil water content within the profile at sowing (modified through pre-season irrigation) were investigated in WA to determine how best to alleviate soil water stress. Additional profile soil water significantly improved crop yields through improved early biomass production, including increased ability of roots to extract water. Wider row spacing enhanced yield in a season of low rainfall, but when average rain fell during the season, pre-season irrigation did not alter the effect of row spacing on grain yield. This indicated that in-season rainfall was the main determinant of differential chickpea performance with row spacing.

In pot experiments, chickpea emergence was optimal at gravimetric soil water content of 17% and delayed when lower than 12% or higher than 23%. Soil strength impeded early root growth at >1 MPa, causing lateral roots to predominate. Seedling shoots tolerated high soil strength better than emerging radicles. In the HBT, with one-pass machine planting, soil water contents in the range 12 to 24% did not limit emergence of chickpea in the HBT across a wide sowing window (22 November to 22 December). However, the optimum sowing date for suitable seedbed conditions and to avoid limiting weather conditions during later vegetative and reproductive growth was found to be between 30 November and 10 December.

Mechanised one-pass row-sowing, permits earlier sowing than under traditional broadcast, full tillage techniques, when soil water contents are higher. In this study the tillage types which
disturbed the soil most, created a better seed-bed under high soil water contents and thus had
greater success in chickpea emergence. Where soil water content in the seed-bed was moderate
to marginal, emergence was not different between zero, strip and line sowing with full rotary
tillage, but was better than traditional broadcast with full rotary tillage. Further, chickpea grain
yields were higher with mechanised row-sowing than with traditional broadcast with full rotary
tillage.

In the HBT, profile soil water content (0 to 50 cm depth) at podding was lower than wilting
point, after this time chickpea accessed water from deeper in the soil profile. In some cases the
extraction of soil water at depth later in the growing season was different between tillage
treatments; these differences were attributed to differences in PPD. The investigation of PPD
and profile soil water content provide insight into possible benefits to alteration in row spacing
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parameters of the water release curve equation (Van Genutchen 1980)

- constant $n$
- constant $m$
- degree of saturation $S_e$
- inverse of air entry potential $\alpha$
- residual water content $\theta_r$
- saturated water content $\theta_s$

penetrometer resistance $Q_p$
percentage clay clay %
percentage sand sand %
percentage silt silt %
physiological maturity $\text{PM}$
plant population density $\text{PPD}$
podding $\text{PD}$
power tiller operated seeder $\text{PTOS}$
precipitation use efficiency $\text{PUE}$
pre-season irrigation $\text{PRE-IRR}$
probability $P$
profile soil water content $\text{SWC}$
rainfall $P$
relative water content $\text{RWC}$
residual maximum likelihood $\text{REML}$
rice retained $\text{RR}$
root growth pressure $\sigma$
root length density $\text{RLD}$
row spacing $\text{RS}$
scaled frequency $\text{SF}$
single pass shallow tillage $\text{SPST}$
soil surface runoff $\text{R}$
soil water potential $\psi$
sowing $S$
sowing date trial $\text{SD}$
specific root length $\text{SRL}$
standard error $\text{S.E}$
strip tillage $\text{ST}$
stubble $S$
Sulphur $S$
summer fallow rainfall $\text{SFR}$
Systemic Acquired Resistance $\text{SAR}$
tillage type trial $\text{TT}$
Transplanted Aman rice $\text{T. Aman}$
triple superphosphate $\text{TSP}$
turgid weight $\text{TW}$
two-wheel tractor $\text{2WT}$
versatile multi-crop planter $\text{VMP}$
volumetric soil water content $\theta_v$
volumetric soil water content at water potential of -10kPa field capacity $\theta_v^{fc}$
volumetric soil water content at water potential of -1500 kPa wilting point \( \theta_{wp} \)

volumetric soil water content from MP406 probe \( \theta_{probe} \)

Western Australia \( \text{WA} \)

zero tillage \( \text{ZT} \)

Zinc \( \text{Zn} \)
List of Botanical Names

barley (Hordeum vulgare L.)
black gram (Vigna mungo L. Hepper)
chickpea (Cicer arietinum L.)
common vetch (Vicia sativa L.)
cotton (Gossypium hirsutum L.)
dry bean (Phaseolus vulgaris L.)
faba bean (Vicia faba L.),
field pea or dry pea (Pisum sativum L.)
lentil (Lens culinaris Medikus)
linseed (Linum usitatissimum L. Griesb.)
lupin (Lupinus angustifolius L.)
maize (Zea mays L.)
marshmallow (Malva parviflora)
mungbean (Vigna radiata L. R. Wilczek)
mustard (Brassica campestris L.)
narbon bean (Vicia narbonesis L.)
pearl millet (Pennisetum glaucum L.)
pigeonpea (Cajanus cajan L.)
rice (Oryza sativa L.)
ricegrass (Oryzopsis holciform (M.B.) Richt.)
ryegrass (Lolium rigidum)
sorghum (Sorghum bicolor L. Moench)
soybean (Glycine max L. Merr.)
wheat (Triticum aestivum L.)
wild radish (Raphanus raphanistrum)
Acknowledgements

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I thank my family of John, Tricia and Narrelle for their encouragement.

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1 Literature review

1.1 Introduction

Chickpea (*Cicer arietinum* L.) was produced across 51 countries during the last 15 years (FAOSTAT 2011). The top producers from 2008 to 2010, each growing >100,000 ha of land and producing >100,000 t, were India, Pakistan, Iran, Australia, Turkey, Myanmar and Ethiopia (FAOSTAT 2011). Chickpea has fluctuated within the top three pulses produced in the last 15 years, the other pulse crops dominating production being dry pea (*Pisum sativum* L.) and dry bean (*Phaseolus vulgaris* L.) (Singh 1997; Kumar *et al.* 2007; Parthasarathy Rao *et al.* 2010). In 2007, 7.9 million t of chickpea grain was produced on 10.2 million ha (Parthasarathy Rao *et al.* 2010). In 2009, the reported area worldwide was 11.5 million ha, producing 10.5 million t (FAOSTAT 2011). Chickpea is therefore an important pulse that can provide protein in otherwise protein-limited diets either due to vegetarianism or unavailability of meat products. Adoption of chickpea into small holder farming systems may alleviate poverty and improve nutrition for resource-poor farming families. In countries where cereal crops (wheat; *Triticum aestivum* L. or rice; *Oryza sativa* L.) dominate the cropping system, chickpea can be grown either as an additional crop in the farming calendar (Bangladesh), or as a break crop instead of a fallow (Australia). In both these systems, the rotational benefits of having a pulse crop such as chickpea in the farming system are: increased soil nitrogen (N), increased soil organic matter, improved weed management, reduced levels of disease, and increased income-earning potential (Singh 1997; Siddique *et al.* 1999).

Various authors have divided the chickpea growing areas worldwide into regions based on geography (Knights *et al.* 2007), climate types (temperate, subtropical) or growing season conditions of rainfall and temperature (Berger and Turner 2007). Berger and Turner (2007) undertook climate analyses of the current chickpea-growing regions based on similarities in annual rainfall, rainfall distribution and temperature and identified two separate climate types where chickpea is grown. These were characterised as a Mediterranean-type group and a summer-dominant rainfall group, with chickpea produced either during the dominant rainfall
season, or post-rainy season, respectively. Characteristics of each are described in Table 1.1. Across these regions, 90% of the chickpea is produced under rainfed conditions and the remaining 10% with irrigation (Knights et al. 2007; Toker et al. 2007).

Table 1.1. The characteristics of the two climate types (Berger and Turner 2007) where chickpea is produced.

<table>
<thead>
<tr>
<th>Rainfall Environment</th>
<th>Rainfall Characteristics</th>
<th>Temperature Characteristics</th>
<th>Country/Region</th>
<th>Main Sowing Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mediterranean-type environment</td>
<td>Consistent, low annual rainfall, winter-dominant rainfall</td>
<td>Low winter temperatures</td>
<td>Central Asia, West Asia and North Africa, Europe, Parts of South and North America (western), Australia (southern)</td>
<td>Coincides with start of rainfall season</td>
</tr>
<tr>
<td>Summer-dominant rainfall environment</td>
<td>High and variable rainfall mostly falling in summer</td>
<td>Moderate to high winter temperatures</td>
<td>South Asia, East Africa, Parts of South and North America, Australia (southern Queensland, northern New South Wales, northern Western Australia)</td>
<td>Post-rainy season</td>
</tr>
</tbody>
</table>

These two climate types are both likely to experience drought, making terminal drought a major abiotic constraint to chickpea production. Where chickpea is sown in the post-rainy season, the crop utilises stored soil water (Siddique et al. 2000) which, depending on crop duration and growing season temperature constraints, may become limiting during pod-filling and lead to terminal drought. The crops grown in the winter-dominant rainfall season are normally sown when the rainfall begins and grow by utilising both stored soil water and seasonal rainfall. These chickpea crops may also be affected by terminal drought. In addition, during periods of little or no rainfall the crop may experience intermittent drought during the growing season. Of the 28 regions (within North and South America, Europe, West Asia and North Africa, East Africa, Australia, South Asia) across both climate types characterised by Berger and Turner (2007) all have drought as an abiotic constraint to production. Across the regions, the abiotic stresses of frost, cold, heat, salinity, alkalinity or waterlogging may exist as
possible constraints. In addition, 13 biotic stresses (including weeds) are listed, but the incidence of each of these varies according to the region and climate.

Both climate type groups have within them a variety of production systems. The greatest distinction in production systems is between developed and developing nations. Developed nations cultivate large parcels of land (>200 ha), and farmers have access to large machinery and mechanised cultivation technology (Kumar et al. 2007). These farmers are also less limited in their access to inputs such as improved varieties, fertiliser, pest and disease management, and research-based management guidelines. Developing nations are characterised by farmers with small land holdings (1 to 10 ha), which may be an aggregation of small dispersed fields, cultivated by either bullock and plough or by two-wheel tractor (also called a power tiller), less availability of quality seed of high productivity varieties and restricted access to fertiliser and other inputs for crop management (Kumar et al. 2007). Additionally, these farmers have low incomes with which to purchase inputs. Management practices for crops are often not defined by regionally-tested research and/or extension of information is limited. Reddy et al. (2007) suggested that to decrease labour costs in crop production in developing nations, there was a need to develop mechanisation of harvesting and threshing operations. Labour is not only constrained by costs but also allocation of family labour to alternate tasks and the timely availability of external labour.

In this thesis, two regions were studied which represented the different climate types and socioeconomic constraints of chickpea farmers. Region one, the western region of Australia in south-west Western Australia (WA) is characterised by the Mediterranean-type climate with winter rainfall dominant, autumn/winter sowing at the beginning of the rainy season, temperate climate, and a well-developed nation production system. Region two was north-west Bangladesh characterised by summer-dominant rainfall, post-rainy season sowing, and warm climate. Bangladesh is a country with a large proportion of its population farming on small land holdings, cultivating with limited mechanisation.
1.2 Chickpea growing environments

1.2.1 South-west Western Australia – Mediterranean-type climate

In Australia, chickpea was not commercially produced until 1979 (Siddique and Sykes 1997). Australia is now the fourth largest producer of chickpea, at 445,000 t annually (FAOSTAT 2011) with most production exported to South Asia (Siddique and Sykes 1997; ABARES 2011a). Chickpea is produced in the summer-dominant rainfall climate type in southern Queensland and northern New South Wales (NSW) and in the Mediterranean-type climate of southern Australia under winter rainfall (includes south-west WA, Victoria and South Australia) (Siddique et al. 2000; ABARES 2011b). Individual farms can be greater than 1000 ha and production is highly mechanised (Knights and Siddique 2002).

In south-west WA, the chickpea is sown after the onset of rain, anywhere from May to July. Chickpea is sown as an alternative crop to wheat, when previously the land may have been left in fallow after wheat crops or sown to a pasture legume (Siddique and Sykes 1997). When compared with other grain legumes produced in south-west WA, chickpea, both desi and kabuli types, are not the highest yielding nor most widely adapted of the crops grown commercially in the region. Desi type chickpea are characterised by small size, angular shape and coloured seed whilst kabuli type chickpea are characterised as large size, ram-head shaped, beige coloured seed (Singh 1987). Field pea (Pisum sativum L.), faba bean (Vicia faba L.), common vetch (Vicia sativa L.) and narbon bean (Vicia narbonesis L.) were identified as high yielding grain legumes adapted to a range of growing regions across south-west WA (Siddique et al. 1999). However, chickpea has been reported to be a higher value grain historically (Siddique et al. 1999), and more recently was reported as having higher grain prices than lupin (Lupinus angustifolius L.) and field pea from 2004 to 2011 (ABARES 2011a). The crop is sown after break of the season rains, and relies on rainfall during the season for crop production. Within the farm cropping system, chickpea can be sown later than other winter crops sown in south-west WA. The mean growing season rainfall (May to October) in a typical chickpea growing area in south-west WA (Merredin, WA), is 192 mm, with the minimum and maximum recorded at 77 mm in 1992 and 286 mm in 1999, respectively (DAFWA 2012), most of which falls
during May to August (Figure 1.1). At sowing, the temperature is between 6 and 20 °C (mean minimum and mean maximum mean temperatures, 1912 to 1985; BOM 2012) and declines subsequently so that the growth stages of flowering and podding are potentially during low temperatures and may also be affected by frost. During grain filling, temperatures begin to increase, rainfall declines, and plant available water in the soil profile can also be minimal resulting in terminal drought.

![Figure 1.1](image)

**Figure 1.1.** The mean monthly rainfall (1903 to 2013) and minimum and maximum temperatures (1966 to 2013) at Merredin, Western Australia. Station Number: 010092, Latitude: 31.48°S, Longitude: 118.28°E, Elevation: 315 m (BOM 2013).

Main constraints to production have been identified as: Ascochyta blight (caused by *Ascochyta rabiei*), cold temperature-related stresses, and terminal drought (Berger 2006). The production of chickpea in south-west WA was significantly reduced from 1999 when Ascochyta blight emerged (Knights and Siddique 2002; Salam *et al.* 2011). Only after the identification of chickpea cultivars resistant to Ascochyta blight did production again increase (Kumar *et al.* 2007; ABARE 2009; ABARES 2011b).

Significant research has been done to improve production of chickpea across growing regions of Australia which included research specific to south-west WA. This began with
studies to determine the potential of chickpea as a crop suited for production in the rainfed environment of south-west WA (Siddique and Sedgley 1986). It was followed by investigations on crop phenology (Thomson et al. 1997), water use efficiency and components of plant transpiration and soil evaporation (Siddique and Sedgley 1987; Thomas and Fukai 1995b; Siddique et al. 2001) as well as radiation use efficiency and canopy development (Thomas and Fukai 1995a; Thomson and Siddique 1997). Specific research has targeted aspects of agronomic management including sowing date, seed rate, seed depth, nutrient management, plant density and arrangement, and weed management (Siddique et al. 1984; Beech and Leach 1988; Siddique and Loss 1999; Riethmuller and MacLeod 2001, 2002; Regan et al. 2003; Felton et al. 2004). Selection for cultivars suited to climatic conditions associated with high temperature and terminal drought have been identified following investigation of the physiological characteristics of chickpea that improve adaptation to water-limited conditions (Leport et al. 1998; Leport et al. 1999) and give economic yields (Behboudian et al. 2001; Leport et al. 2006; Fang et al. 2010). Assessment of land-use suitability for chickpea production has been completed across south-west WA (van Gool et al. 2004; White et al. 2006). Documents recommending agronomic management practices for farmers have been produced for the growing regions in the northern and the southern agriculture regions of south-west WA (Loss et al. 1998; Harries et al. 2005b; Harries et al. 2005a). Recommendations include advice on: soil type selection, chickpea variety selection, sowing date, seed rate, spacing and depth, rhizobial inoculation, fertiliser, pest and disease management, and crop harvesting.

1.2.2 High Barind Tract in Bangladesh – Summer-dominant rainfall

Pulse crops are an important source of protein across Bangladesh. In 2009, production of chickpea totalled 6,551 t from 8,177 ha (FAOSTAT 2011). In 1999, there was a major decline in chickpea production due to the incidence of Botrytis Grey Mould (BGM) caused by Botrytis cinerea (Johansen et al. 2006): area sown decreased from 84,025 ha in 1998 to 18,219 ha in 1999, while production decreased from 59,900 to 15,000 t (FAOSTAT 2011). Chickpea is an important staple food for Bangladesh, which imports increasing amounts to meet demand (Johansen et al. 2006). In 2009, 157,915 t of chickpea was imported into Bangladesh.
(FAOSTAT 2011). This thesis is interested in the geographic region of the High Barind Tract (HBT) of Bangladesh which is in the north-western Rajshahi division of Bangladesh. North-western Bangladesh has regular food shortages and dietary imbalances. The HBT covers 2,200 km² of mostly upland gently undulating topography with terraced landform and high clay content in the soil (Musa et al. 2001). Soils in the HBT have a silty clay texture, acid to neutral pH in the surface and a neutral to alkaline soil pH below 20 cm (Joshi et al. 2008; Haque et al. 2010). In the acid HBT soils, molybdenum (Mo) was found to limit nodulation of chickpea and therefore limit access to nitrogen leading to yield penalties (Johansen et al. 2005). Other micronutrients commonly deficient for legumes, including zinc (Zn), boron (B) and sulphur (S), were not found to be limiting in this region (Johansen et al. 2005; Harris et al. 2008).

In the HBT of Bangladesh, there are three distinct seasons: (i) the kharif I season from late March to early June, a hot summer period with heat storms, (ii) kharif II from June to September when the south-west monsoon is active, and (iii) the rabi or winter season that is dry and cool. The mean annual rainfall over 45 years at the district centre of Rajshahi is 1,538 mm with most, 1,290 mm, falling from June to October (BARC 2011). In the rabi season from November to March, usually little to no rainfall occurs. Temperatures are lowest early in the rabi season and then climb again from late January through to June (Figure 1.2). For the chickpea growing season of November to March the mean rainfall is 71 mm, and heat storms in the kharif I can cause rainfall at harvest during March (BARC 2011).
Figure 1.2. The mean monthly rainfall and minimum and maximum temperatures in Rajshahi Bangladesh (BARC 2011). Mean of the years 1994 to 2008, Rajshahi Station. Latitude: 24.35°N, Longitude: 88.56°E, Elevation: 20 m.

The cropping calendar in the HBT commonly has kharif season rainfed transplanted rice (often referred to as Transplanted Aman rice (T. Aman)), grown from June to November, followed by fallow or irrigated rice, wheat, or vegetables grown in the rabi season (Musa et al. 2001; Johansen et al. 2008a). In upland areas where irrigation is not possible, chickpea may be produced during the rabi season. Ali et al. (2007) determined that in 2000 to 2002 remuneration from chickpea was higher than for other rabi season crops such as wheat, mustard (*Brassica campestris* L.), barley (*Hordeum vulgare* L.), linseed (*Linum usitatissimum* L. Griesb.) and lentil (*Lens culinaris* Medikus). These crops rely on residual soil water left in the profile from the monsoon period (Gaur et al. 2008; Johansen et al. 2008a). The common cropping patterns which include chickpea in the HBT are:

1) rice (April to August), fallow (August to October), chickpea (November to April); and

2) fallow (April to June), rice (July to December), chickpea (December to April) (Kabir et al. 2009).
These cropping patterns include the use of rice sown in the early rainy season (Aus rice) and rice grown during the main rainy season (T. Aman rice). Alternative cropping programs may include mungbean (Vigna radiata L. R. Wilczek) sown between a winter legume crop and T. Aman rice, or a single crop of T. Aman rice (Ali 2000; Pande et al. 2007). Recommended sowing time for chickpea in Bangladesh is mid-November (Kabir et al. 2009), however, for the HBT recommendations are for sowing in the last week of October to the first week of November (BARI 2010). Other authors suggest that the timing of chickpea sowing could however be any time in November, when the field is dry enough after the harvest of T. Aman rice (Johansen et al. 2008b). Across South Asia, chickpea is sown from October to November and matures between February and April; crop duration can range from 110 to 170 days (Pande et al. 2007).

Notwithstanding these recommendations, in the HBT of Bangladesh a common cropping pattern is T. Aman rice followed by chickpea so that the sowing time of the latter is dependent on timely harvest of the rice crop, which even with early maturing rice varieties will be early November, pushing sowing of chickpea to mid-November or later. The mean end date of the monsoon rice crop sown from 1947 to 1984 was 28 December, with a 25% probability of it being 3 December (Brammer 2000; Riches 2008). Sowing dates recommended for chickpea grown in India are mid-October to mid-November, with deviations from this causing reduced yield. More specific optimum sowing dates within this time period are recommended for various locations. However, the rice-chickpea cropping system often has a sowing date of chickpea beyond that recommended due to the late harvest of rice (Saxena 1987). Optimum sowing dates are those that match the crop’s growth requirements for water, temperature and day length against important crop requirements for germination, vegetative and reproductive growth (Saxena 1987). Another factor to consider in selecting sowing date is disease risk. Johansen et al. (2008a) recommended a strategy for integrated crop management which was essentially a package that promoted practices to limit the infestation of BGM in Bangladesh chickpea crops. The recommended sowing date for this package was between late November and early December.
Chickpea production in the HBT began as an alternative to leaving land fallow (Kumar et al. 2007). Experiments in the HBT in the 1980’s initially led to 100 ha of chickpea sown in 1981 expanding to 14,000 ha sown in 2001 (Kumar et al. 2007). Ali (2000) reported that 55 % of the 144,000 ha of land in the HBT remained fallow during the rabi season, and 10,000 ha was sown to chickpea. These crops were sown as soon as possible after rice harvest while the soil surface was moist. A benefit of sowing chickpea in the HBT during this period is the dry climate which helps avoid foliar diseases (Kumar et al. 2007). The average yield across Bangladesh from 1971 to 2006 was 0.72 t/ha (MOA 2007). Musa et al. (2001) reported that chickpea yields of 1 t/ha were possible in the HBT.

The chickpea crop sown into the rabi season in the HBT is therefore sown into a soil profile which is potentially full of stored water following the harvest of the kharif rice crop. Profile soil water content in the HBT has been reported to be between 125 to 218 mm/m of soil in October and drops to between 24 to 119 mm/m soil in November, depending on location and soil series within the HBT (Idris and Munirul Huq 1987). Riches (2008) suggests that any crops grown on residual soil moisture in the rabi season would need to be early maturing. At sowing, mean maximum temperatures are 29 °C in November and 25 °C in December with minima of 17 and 12 °C, respectively (Figure 1.2) (BARC 2011). Crop establishment can be limited by soil surface drying affecting the number and vigour of emerged plants. As the season continues, early crop growth may be affected by low temperatures. In January, the mean minimum and maximum temperatures are 11 and 24 °C, respectively. Minimum temperatures of 14 to 16 °C delay the formation of flowers and pods (Croser et al. 2003; Berger et al. 2004). Towards the end of the growing season, temperatures rise to maxima averaging 33 to 35 °C which leads to high evapotranspiration, at a time when potentially there is little stored soil water remaining available for the chickpea plant. This can lead to terminal drought at pod-filling (exacerbated by earlier delays in establishment) and lower yield potentials (Summerfield et al. 1984; Kumar and Abbo 2001). There is only a 26 % chance of receiving ≥100 mm of rainfall during the growing season from November to March (BARC 2011); therefore the crop must obtain virtually all of its water requirement from the residual water stored in the soil in most years.
During the rabi season in the HBT, irrigation and high rainfall are unlikely so that waterlogging, to which chickpea is very susceptible, is not normally a problem. However, waterlogging can occur at sowing when excessive water is in the seed-bed, and persists for longer further north of the HBT in Thakurgaon and Panchagarh, the soil may remain wet due to a shallow standing water table, low temperatures and fog which prevent evaporation from the soil surface (Marufuzzaman et al. 2010).

1.2.2.1 Cultivation practices

South Asia is characterised by landholders with dispersed holdings of small parcels of land with the potential for production of two to three crops per year. Often the landholders are subsistence farmers with little finance available for equipment and infrastructure. No-till farming in developing countries is constrained due to the predominance of resource-poor small holder farmers, small field sizes, lack of access to herbicides for weed control and lack of appropriate seeding equipment (Lal 2007). The crops produced need to be targeted to consumption by the household with excess production having a market potential. Any recommendations for cropping system management need to keep these limitations in mind. Socioeconomic factors can limit the availability of resources, such as tractors and planters, and therefore the tillage types available. The soil type, climate and cropping system dictates the method of tillage which will allow optimum soil conditions required for subsequent crop growth and continued production. Hence the type of tillage selected for a region tends to be designed for that location and purpose (Lal 1994).

In Bangladesh, the traditional broadcast system of cultivation has been replaced by increasing levels of mechanisation with small two-wheel tractors (2WT) with rotary tillage attachments (Haque et al. 2004). Rotary tillage is used in rice production to puddle the land for rice transplanting and for full tillage associated with broadcast-sowing of other crops (M.E. Haque, R.W. Bell, A.K.M Islam, K.D. Sayre and M.M. Hossain, personal communication). Two-wheel tractors are also used in the region as power sources for purposes such as transport, irrigation, winnowing and threshing (Hobbs et al. 1997; Haque et al. 2004; Roy et al. 2009). The development of 2WT with planters has been ongoing in Bangladesh since 1995 (Roy et al.
2009; Johansen et al. 2012). The original 2WT with planter was referred to as the power tiller operated seeder (PTOS) which provided full but shallow rotary tillage and delivered seed only behind tines (furrow openers) in a single pass. It was subsequently termed single pass shallow tillage (SPST) (Johansen et al. 2012). Original SPST units had no fertiliser delivery option and the fertiliser was broadcast before the sowing operation. Subsequently, along with development of zero and strip tillage options for 2WT, fertiliser boxes were added to the planter such that fertiliser could be placed with seed behind tines. By retaining up to 50% of the rotary blades directly in front of the tines the SPST planter could be reconfigured as a strip tillage (ST) planter (Justice et al. 2004; Roy et al. 2004; Roy et al. 2009). By removing all of the rotary blades it was possible to perform zero tillage (ZT) with 2WT, whereby only the tine opened the furrow and seed and fertiliser were delivered behind the tine (Haque et al. 2004). These tillage options are further elaborated in Section 1.4.2.3. Benefits of this sowing technology were targeted, albeit shallow, placement of seed, less time, fuel and labour required, and associated monetary savings.

1.3 Abiotic, biotic and socioeconomic constraints

The two climatic regions chosen for this present study experience both similarities and differences in the abiotic, biotic and socioeconomic constraints to chickpea production. These constraints will be discussed with particular emphasis on the solutions developed in the regions to overcome stresses. Solutions to the various constraints can be categorised as: agronomic, genetic, or social and extension. In this thesis, particular attention is paid to the abiotic constraints to chickpea plant establishment, in-season crop growth and final crop yield. The current status of research and solutions for the biotic and socioeconomic constraints will only be briefly addressed in this section of the thesis.

1.3.1 Constraints – south-west Western Australia

Chickpea produced in south-west WA encounters a number of abiotic and biotic constraints that can limit production Table 1.2. The main abiotic constraints are drought, cold and waterlogging (Berger 2006). The combination of limited in-season rainfall and rising spring
temperatures lead to terminal drought in chickpea crops (Berger and Turner 2007). The main biotic constraints across Australia are the fungal diseases, Ascochyta blight and BGM (Knights and Siddique 2002; Salam et al. 2011). Other pests and diseases which may occur across Australia are: the insect pod-borer (*Helicoverpa armigera*), the viruses cucumber mosaic and alfalfa mosaic, and the fungus sclerotinia stem rot (caused by *Sclerotinia sclerotiorum* and *S. trifoliorum*) (Hamblin et al. 2000). Berger and Turner (2007) listed weeds as another main constraint in Western Australia.

### Table 1.2. Constraints to chickpea production in south-west Western Australia (WA).

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Consequence</th>
<th>Alleviation</th>
<th>Solution</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited in-season rainfall and rising spring temperatures.</td>
<td>Intermittent and terminal drought.</td>
<td>Drought escape, postponement or tolerance.</td>
<td>Genetic Agronomic</td>
<td>(Leport et al. 1998; Leport et al. 1999; Behboudian et al. 2001; Fang et al. 2010)</td>
</tr>
<tr>
<td>Cold</td>
<td>Longer period in vegetative growth stage. Adverse conditions for flower and pod development.</td>
<td>Develop chickpea cultivars with chilling tolerance.</td>
<td>Genetic</td>
<td>(Croser et al. 2003; Berger et al. 2005; Berger 2007)</td>
</tr>
<tr>
<td>Botrytis Grey Mould&lt;sup&gt;1&lt;/sup&gt;, Ascochyta blight&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Crop losses.</td>
<td>Integrated crop management, development of resistant varieties.</td>
<td>Agronomic Genetic</td>
<td>(Davidson and Kimber 2007; Gaur et al. 2007; Pande et al. 2007; Bretag et al. 2008; Salam et al. 2011)</td>
</tr>
</tbody>
</table>

<sup>1</sup>Botrytis Grey Mould caused by *Botrytis cinerea*<br><sup>2</sup>Ascochyta blight caused by *Ascochyta rabiei*

#### 1.3.2 Constraints – High Barind Tract, Bangladesh

In the HBT there are abiotic, biotic and socioeconomic constraints to the production of rainfed rabi season chickpea crops (Rahman et al. 2000; Joshi et al. 2002; Orr et al. 2008). Across South Asia, chickpea is grown in marginal environments where there is slow uptake of technology on poor soils under erratic climate conditions (Harris et al. 1999; Harris et al. 2005; Parthasarathy Rao et al. 2010). These constraints may also be common to other rainfed rabi crops produced in the region (Joshi et al. 2002). In addition, in the HBT chickpea yields decrease due to surface soil drying and declining temperatures in the rabi season, leading to
delayed podding and flowering, risk of terminal drought, damage by chickpea pod-borer and storm damage in late March when a late sown crop may still be standing in the field (Johansen et al. 2008b). Table 1.3 outlines these constraints and the solutions which have been developed to overcome them.
<table>
<thead>
<tr>
<th>Constraint</th>
<th>Consequence</th>
<th>Alleviation</th>
<th>Solution</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low and uncertain in-season rainfall.</td>
<td>Reliance on residual water for crop requirements, can lead to terminal drought if stores are not adequate.</td>
<td>Plant breeding strategies to develop deep rooting chickpea, and short duration varieties.</td>
<td>Genetic</td>
<td>(Kumar and Abbo 2001; Chaturvedi and Ali 2004; Kashiwagi et al. 2005)</td>
</tr>
<tr>
<td>Soil hardness as a result of soil puddling for rice cultivation.</td>
<td>Hard pan develops at 10 to 15 cm, reduces permeability of water and restricts root growth.</td>
<td>Plan time of sowing when soil water at field capacity to allow penetration of rabi season crops.</td>
<td>Agronomic</td>
<td>(Johansen et al. 2008b)</td>
</tr>
<tr>
<td>Soils deficient in molybdenum (Mo).</td>
<td>Inadequate nitrogen (N) fixation due to poor nodulation and nutrient deficient soils.</td>
<td>Mo and Rhizobium applied by seed priming Program to provide Rhizobium and Mo to farmers.</td>
<td>Agronomic Socioeconomic</td>
<td>(Johansen et al. 2005; Harris et al. 2008)</td>
</tr>
<tr>
<td>Diseases of chickpea, Botrytis Grey Mould¹, collar rot² and Fusarium wilt. Insects of pod-borer (Helicoverpa armigera).</td>
<td>Yield instability, reduced plantings.</td>
<td>Integrated crop management, development of resistant varieties.</td>
<td>Agronomic Genetic</td>
<td>(Johansen et al. 2006; Gaur et al. 2007; Harris et al. 2008; Hossain et al. 2008; Johansen et al. 2008a; Johansen et al. 2008b)</td>
</tr>
<tr>
<td>Lack of short duration rice varieties.</td>
<td>Late sowing of following chickpea crop leading to terminal drought and low yield potential.</td>
<td>Development of early maturing rice varieties; technology of direct seeding rice.</td>
<td>Genetic Agronomic</td>
<td>(Joshi et al. 2008; Mazid et al. 2008)</td>
</tr>
<tr>
<td>Lack of short duration chickpea and rabi crop varieties.</td>
<td>Pod-filling stage potentially occurs during high temperatures when little soil water is available to plants, which can lead to low yields.</td>
<td>Sow early. Development of short duration varieties.</td>
<td>Agronomic Genetic</td>
<td>(Johansen et al. 1997; Kumar and van Rheenen 2000; Serraj et al. 2003)</td>
</tr>
</tbody>
</table>
Table 1.3. Continued

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Consequence</th>
<th>Alleviation</th>
<th>Solution</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A weak public extension program.</td>
<td>Leads to insufficient knowledge by farmers for overall production and storage.</td>
<td>Integrated crop management guidelines and plans. Training packages developed for all aspects of crop production. On-farm participatory research to accelerate adoption of technology.</td>
<td>Socioeconomic</td>
<td>(Musa et al. 2001; Joshi et al. 2002; Johansen et al. 2008b; Musa et al. 2008)</td>
</tr>
<tr>
<td>Labor shortages in addition to current labor-intensive and slow farm practice.</td>
<td>Miss the optimum sowing window (agronomic and surface soil water) leading to poor plant stands and low yields due to terminal drought. Land remains fallow.</td>
<td>Mechanised row-sowing powered by two-wheel tractors being developed.</td>
<td>Agronomic</td>
<td>(Hobbs et al. 1997; Haque et al. 2004)</td>
</tr>
<tr>
<td>Poor farmers with lack of capital to purchase inputs of seed, fertiliser and pesticides.</td>
<td>Land remains fallow.</td>
<td>Minimum tillage technology, targeted placement of seed and fertiliser.</td>
<td>Agronomic</td>
<td>(Haque et al. 2004; Justice et al. 2004)</td>
</tr>
<tr>
<td>Lack of markets for the low volume of crop produce.</td>
<td></td>
<td>Small scale seed dehusking mills to value-add product.</td>
<td>Socioeconomic</td>
<td>(Bell et al. 2012)</td>
</tr>
</tbody>
</table>

*Botrytis Grey Mould caused by Botrytis cinerea

*collar rot caused by the fungus Sclerotium rolfsi

1.3.3 Constraints common to both regions

The production of chickpea across the two regions encounter similar limitations with regard to crop establishment, within-season temperature stresses and terminal drought. The events that lead to poor germination, poor crop growth and terminal drought are different across the two regions and are summarised in Table 1.4. In the summer-dominant rainfall environment of the HBT, the initial profile soil water content is potentially high, especially in areas where the monsoon season has just finished. High temperatures and high evaporation rates of the soil surface after the harvest of the rice crop can lead to a rapidly drying seed-bed which can limit chickpea germination and emergence. The crop has to rely on extracting available soil water (residual soil water left after the monsoon period) from the soil profile during the entire growing
season as there is limited in-season rainfall (Rahman et al. 2000; Gaur et al. 2008). In the Mediterranean-type environment dominated by winter rainfall, there are high temperatures and limited antecedent rainfall during the preceding summer season, hence stored soil water is potentially low. Sowing of chickpea will normally be after onset of rainfall which wets the surface soil enough to allow germination, and if winter rainfall is sparse mid-season plant water stress can occur. In both environments, during crop growth there is continued depletion of the available stored soil water by the chickpea crop in combination with increasing temperatures during pod-filling which can lead to conditions of terminal drought.

Within the growing season in both environments chickpea may encounter temperatures, both high and low, that limit crop growth. In the HBT of Bangladesh, the weather constraints of cold and heat impact on different growth stages of chickpea. Chickpea is sown after rice harvest occurs, which often causes late sowing and the potential for low temperatures during emergence and vegetative growth and high temperatures during pod and seed development (Chaturvedi and Ali 2004). In south-western WA, May is the recommended sowing time for the northern region but June for crops further south (Regan and Siddique 2006). The chickpea crop is likely to experience low temperatures at flowering and podding which can lead to flower and pod abortion especially in the southern part of the region (Clarke and Siddique 2004; Berger et al. 2005). As the season progresses, higher late spring to early summer temperatures can affect yield formation. In combination with low in-season rainfall this can cause intermittent and terminal drought.
Table 1.4. The characteristics of the abiotic constraints which can lead to poor crop establishment, low temperature stress and/or terminal drought to chickpea production in south-west Western Australia (WA) and the High Barind Tract (HBT) of Bangladesh. These two regions represent the two main climate types described in Berger and Turner (2007) for chickpea production, viz the Mediterranean-type environment and the summer-dominant rainfall environment.

<table>
<thead>
<tr>
<th></th>
<th>South-west WA</th>
<th>HBT Bangladesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate type</td>
<td>Mediterranean-type environment</td>
<td>Summer-dominant rainfall environment</td>
</tr>
<tr>
<td>Sowing time</td>
<td>Autumn/winter chickpea sown after summer fallow.</td>
<td>Winter season chickpea sown after monsoon rice.</td>
</tr>
<tr>
<td>Profile soil water content at sowing</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Soil water content at germination</td>
<td>If rainfall does not occur low soil water in the surface for germination.</td>
<td>High surface soil evaporation leads to low surface soil water content for seed germination.</td>
</tr>
<tr>
<td>Growing season rainfall</td>
<td>Average May to October rainfall, 209 to 438 mm across south-western WA (Siddique et al. 1999).</td>
<td>Average November to March rainfall, 71 mm Rajshahi, HBT, Bangladesh (BARC 2011).</td>
</tr>
<tr>
<td>Low temperature stress</td>
<td>Potentially limiting during flowering or podding, leading to flower and pod abortion.</td>
<td>Potentially limiting during emergence and early seedling growth, affecting early seedling vigour.</td>
</tr>
<tr>
<td>High temperature stress</td>
<td>Potentially limiting during pod set and seed development.</td>
<td>Potentially limiting during pod set and seed development.</td>
</tr>
<tr>
<td>Onset of drought stress</td>
<td>In conditions of low or intermittent growing season rainfall, terminal drought stress may occur.</td>
<td>With increasing soil water deficit, terminal drought stress may occur.</td>
</tr>
</tbody>
</table>

1.3.4 Factors affecting crop establishment

In both climatic regions there is potential for low soil water content at sowing which may limit seed germination, emergence and the plant population at establishment. Seedling establishment comprises three critical stages where soil physical factors can affect success, namely: seed germination, seedling emergence, and seedling root growth. Soil physical factors which affect all three of these, to varying degrees, are soil strength, soil water, soil aeration, soil temperature and light (Cardwell 1984; Cook et al. 1995). When seed germination and seedling emergence are rapid and roots penetrate into the subsurface soil quickly there is greater chance
of achieving adequate plant stands, and ultimately good yields (Fyfield and Gregory 1989; Kirkegaard et al. 1992; Nasr and Selles 1995; Harris et al. 1999; Soltani et al. 2006).

Seed germination is most affected by soil water content, soil water potential and the soil temperature. Seed germination is activated by water absorption of the seed which occurs in three stages (Hadas and Russo 1974; Hadas 1977; Cardwell 1984; Etherington and Evans 1986; Hadas 2004; Fenner and Thompson 2005):

1) imbibition stage when water penetrates the seed coat and is absorbed by the embryo and the dry seed absorbs water at a rapid rate: this is the same for viable and non-viable seeds;

2) the transition or activation phase, when enzymatic transformations and initiation of meristem activity take place: this is the same for viable and non-viable seeds and there is low water uptake during this phase; and

3) the growth phase which is a second rapid water uptake phase, when the radicle and coleoptile or hypocotyl emerge through the seed coat if the seed is viable.

The rate of imbibition is controlled by factors associated with both the seed and the liquid or gas phase of water surrounding it in the soil matrix. The permeability of the seed coat and the proportion of the seed components which swell (proteins, cellulose and pectins) in comparison to those which do not swell (starches and lipids), are properties of the seed which affect imbibition (Cardwell 1984; Fenner and Thompson 2005). The water uptake of the seed occurs when the water potential of the seed is lower than the water potential of its surroundings (Evans and Etherington 1991). The initial movement of water from the soil to the seed is normally quite rapid as the seed has very low water potentials in comparison to the soil around it. The resulting water potential gradient from seed to soil is quite large at the onset of germination and decreases as the seed hydrates (Hadas 2004). This will coincide with the first growth phase of germination, imbibition. During the second stage of germination, the transition phase, there is a pause in water uptake. In the third phase, the growth phase has an increased requirement for water when the seed starts to develop the radicle and root hairs and increased uptake of water from the soil is required (Hadas 2004).
In the soil matrix, factors such as soil water potential, soil hydraulic conductivity, and seed-soil contact may increase or decrease imbibition and time to germination (Hadas and Russo 1974; Hadas 1977; Cardwell 1984). These in turn are controlled by soil physical factors such as soil particle size distribution, soil pore diameters and aggregate size (Collis-George and Sands 1959; Dasberg and Mendel 1971; Atkinson et al. 2007). These control the movement of water to the seed, through the seed-soil contact, the hydraulic conductivity and the water holding capacity of the soil. At decreasing soil water content and increasing soil water potential, germination is delayed or fails. The range of soil matric potentials across which a seed will germinate will differ with soil texture (Collis-George and Sands 1959; Dasberg and Mendel 1971). A fine textured soil is likely to have a higher proportion of smaller aggregates and finer pores leading to better seed-soil contact and movements of water to the seed than a coarse textured soil (Brown et al. 1996; Atkinson et al. 2007).

Cardwell (1984) suggests that the water in the gaseous or liquid phase influences imbibition of the seed, but when the seed is placed in the soil the liquid phase is more important. In situations where seed-soil contact is limited, water vapour can be the main source of water imbibition to the seed for successful germination (Wuest et al. 1999). Germination under these circumstances may be delayed in proportion to the distance between the seed and liquid water as uptake of water vapour to the seeds is relatively slow (Atkinson et al. 2007; Wuest 2007). The minimum seed moisture required for chickpea germination was reported as 72 to 75 % of the seed dry weight (Hadas and Stibbe 1973; Hadas and Russo 1974). At soil water potentials less than -380 kPa, the rate of water uptake of chickpea seeds and final germination was reduced (Hadas 1976). Singh and Afria (1985) also found the rate of chickpea seed germination decreased as external soil water potential decreased to -750 kPa and was not possible at -1000 kPa. In addition, the kabuli chickpea varieties were more sensitive to water stress than the desi type, with the critical limit of germination being at soil water potentials of -500 and -750 kPa, respectively (Singh and Afria 1985). Hadas (2004) defined a critical soil water potential as the external water potential value at which seeds cannot reach the critical hydration level. For chickpea this value was reported as -600 kPa in the soil, which equates to -2000 kPa in the seed (Hadas and Stibbe 1973; Hadas and Russo 1974). The rate of germination will be
increased by values of water potential greater than this critical water potential, but the final percentage of germination may still not reach 100 % (Hadas and Russo 1974).

Seedling emergence has two important components (i) the development of the radicle and subsequent root growth, and (ii) development of the epicotyl (in the case of chickpea). Both are affected by soil water content, strength, bulk density and aggregate size. However, the sensitivity of these two components to soil physical conditions are not the same, and also vary among species (Fyfield and Gregory 1989; Dracup et al. 1993). Similar to chickpea seed germination, the range in gravimetric soil water contents ($\theta_g$) for chickpea emergence was wide, 9 to 34 %, and emergence was delayed or declined with soil drying (ICRISAT 1981; Saxena et al. 1983; Sharma 1985; Johansen et al. 1997; Hosseini et al. 2009a). Studies have found that the rate of chickpea emergence declined as soil water content dried below field capacity but early seedling growth tolerated soil water potentials to -500 kPa (Sharma 1985). Hosseini et al. (2009a) found that the larger seeded kabuli type (macrosperma) chickpea was able to have higher daily growth rates than the smaller desi types (microsperma) when the soil water content was near field capacity. This early vigour advantage was lost at dry soil water conditions, although both types underwent reduced early growth as soil water content decreased. Emergence of seedlings (lupin and mungbean) has been reported to tolerate a narrower range in soil water potential than the seed germination (Fyfield and Gregory 1989; Dracup et al. 1993). Differences in chickpea seedling emergence under water stress have been quantified across genotypes, soil types and environments. It was suggested that this difference could be used to screen chickpea genotypes for their ability to germinate when seed-bed moisture was limiting while maintaining early vigorous growth (ICRISAT 1981; Saxena et al. 1983; Hosseini et al. 2009a).

A requirement for plant growth is that the volume of gas filled pores should be at least 10 % (Dexter 1988), and at an air-filled porosity of 15 % root growth is not limited by oxygen supply (Richards and Cockroft 1974; Tisdall and Adem 1988; Cockroft and Olsson 1997). During germination and emergence, oxygen is required for continued metabolic activity and respiration for the seed (Hadas 2004). At high soil water contents, diffusion of oxygen can be limited (Dasberg and Mendel 1971) as the rate of oxygen diffusion through air is $10^4$ times greater than
the rate through water (at 20 °C). The diffusion of oxygen through the seed testa and pericarp can also limit oxygen supply to the seed, and the accumulation of water films around the seed will further exacerbate oxygen uptake (Hadas 2004).

The soil properties such as soil particle size distribution, the size and proportion of each soil pore diameter class and aggregate size not only affect the movement of water to the seed but also the resultant soil bulk density and soil strength. The development and emergence of the epicotyl and the extensions of early root growth are affected by soil bulk density, soil strength and aggregate size. As soil strength and bulk density increase, germination and emergence can be delayed and elongation rates of roots decreased (Materechera et al. 1991; Nasr and Selles 1995). The packing of soil aggregates and the size and shape of the voids between and within the aggregates can also alter early root growth and seedling emergence. The epicotyl emergence of seedlings can be blocked under surface crusts or under large soil clods (Dorsainvil et al. 2005). Where emergence of chickpea seedlings is limited by an impeding layer, such as a soil crust, they have been found to swell to increase their epigeal diameter to exert a greater force to allow them to push through the impeding layer (Sivaprasad and Sundara Sarma 1987).

Temperature can affect germination rate and final germination percentage. The cardinal temperatures for germination are defined as the minimum, optimum and maximum temperatures for germination of a species or cultivars within a species (Hadas 2004). The first stage of imbibition has lower sensitivity to temperature than the next two phases which are more dependent on temperature because of the biochemical processes involved.

In planting field crops such as chickpea, time of sowing is decided based on soil conditions, weather patterns and the time of year. Chickpea germination has been reported to occur over the range of 10 to 45 °C, with optimal ranges between 20 to 29 °C reported by Soltani et al. (2006) and 14 to 26 °C reported by Roberts et al. (1985). The earlier section (Section 1.2) on chickpea growing environments noted that at sowing minimum and maximum temperatures are between 15 and 35 °C in Bangladesh (Figure 1.2) and 6 and 20 °C in south-west WA (Figure 1.1).
1.3.5 Manifestations and mechanisms of temperature and drought stress

In both regions, temperatures within the chilling range (-1.5 to 15 °C) can affect chickpea growth during the vegetative and reproductive growth stages (Croser et al. 2003; Clarke and Siddique 2004). The base temperature for germination of chickpea is 0 °C, and is not a limiting factor in either region (Croser et al. 2003; Bennett 2004). In the HBT during chickpea growth, low temperatures are possible during emergence and early seedling growth, which can delay emergence and decrease the rate of seedling growth and nodulation (Johansen et al. 2008b). In the vegetative stage of growth, low temperatures may prevent early vigorous growth and delay flowering. Temperatures above 10 °C have been reported to induce a transition from the vegetative to the reproductive growth phase (Croser et al. 2003; Chaturvedi and Ali 2004; Nayyar et al. 2005; Kumar et al. 2010). Early biomass production may be similar between chickpea which experiences low temperatures or warmer temperatures during early growth. The longer time spent in the vegetative phase of growth in cooler temperatures can negate the shorter duration and more rapid vegetative growth of chickpea grown in warmer temperatures (Summerfield et al. 1984). However, the lengthened duration of vegetative growth under low temperature can expose the chickpea plant to limiting temperature and soil water conditions in the latter part of the growth phase.

Temperatures of less than 16 °C can delay pod set and below 10 to 12 °C prevent podding in chickpea (Berger et al. 2004; Clarke et al. 2004). In southern Australia, including WA, low temperatures are likely during the flowering phase which can delay flowering and cause floral abortion and during reproductive growth there will be delays to podding, leading to low pod and seed set (Siddique and Sedgley 1986; Clarke and Siddique 2004; Berger et al. 2005; Toker et al. 2007). Poor pod set has been reported in northern India when temperatures are 15 to 20 °C in the day and 8 to 10 °C at night (Saxena and Johansen 1988; Kumar et al. 2010). Depending on the time of sowing in the HBT, flowering and reproductive growth in January could encounter similar limiting temperatures (Figure 1.2). The indeterminate flowering of chickpea means that as long as temperatures are less than 14 to 16 °C, flowering and flower abortion will continue until temperatures rise to be non-limiting. In south-west WA, delays to podding are calculated to be 12 days for every 1 °C decrease from 14 to 10 °C (Berger et al. 2005). This can delay pod
set of the plant for one to two months (Croser et al. 2003). The low temperatures lead to extension of the duration of chickpea growth: seed filling is then likely to be in a period of water stress as reserves of profile soil water have been used, and there is little in-season rainfall, placing the chickpea crop under terminal drought. A solution to the low temperature stress includes developing chickpea cultivars with improved chilling tolerance (Croser et al. 2003; Berger 2007). In controlled environment studies, it was found that whilst the cold tolerant varieties could set pods during severe and mild cold spells, subsequent seed growth was equally limited in cold tolerant and sensitive cultivars (Srinivasan et al. 1998). These chilling tolerant cultivars have been included in experiments which determined how low temperatures (<15 °C) affect the development and reproductive function of the chickpea flower (Clarke and Siddique 2004). Further studies determined that some wild Cicer germplasm has greater tolerance to low temperatures during reproductive growth (Berger et al. 2005). Cold tolerant traits in wild chickpea germplasm may be useful in breeding programs to improve cold tolerance in modern chickpea cultivars.

In both the HBT and south-west WA, near the end of the growing season the chickpea crop matures under increasing temperatures and decreasing profile soil water content, leading to terminal drought stress. Drought stress leads to decreased length of growing season, delays to flowering and reduced dry matter production, water use efficiency, plant height and seed yield (Berger 2007). Increasing drought stress during the reproductive phase leads to early senescence and reduction in pod and seed development, leading to reduced yield potential (Summerfield et al. 1984; Wang et al. 2006; Berger 2007; Gaur et al. 2008). Losses of seed yield are greater when the stress is during the pod development stage rather than during the flowering stage, as plants recover better when stress is during the flowering phase relative to the reproductive growth phase (Gan et al. 2004; Wang et al. 2006). Drought stress during early pod development can affect pod abortion more than drought stress later in reproductive growth (Leport et al. 2006). High temperatures are required for chickpea plants to mature and is preferred later in the growing season (Wang et al. 2006). However, when heat stress occurs early, during reproductive growth, the chickpea plants can experience forced maturity and reduced pod and seed development (Chaturvedi and Ali 2004). High temperatures can reduce
pod set by reducing pollen viability (Devasirvatham et al. 2010). High temperatures during reproductive growth exacerbate the problem of drought stress, but even with non-limiting soil water, high temperatures alone can limit chickpea yields (Summerfield et al. 1984).

Chickpea has been recognised to have three strategies for drought resistance, these being: (i) escape, (ii) postponement or avoidance, and (iii) tolerance (Turner et al. 2001; Toker et al. 2007). When the chickpea crop matures within a limited growing period before the onset of drought, it is termed drought escape. Genetic traits of the chickpea which allow drought escape are early vigour and early maturity (short duration varieties). Early sowing may assist in drought escape. These all combine to allow crop growth before the onset of terminal drought, and as such the crop duration must match the period of available soil water (Johansen et al. 1997). Drought postponement is through mechanisms whereby the chickpea plant maintains its water uptake and reduces water loss. This can be through physical characteristics of the plant such as large root systems for water uptake and smaller leaf area which can limit water loss via transpiration (Toker et al. 2007). The chickpea plant also minimises water loss whilst continuing water uptake through the control of stomatal conductance, abscisic acid accumulation and osmotic adjustment. Reduced stomatal conductance and abscisic acid accumulation both decrease water loss through transpiration by triggering the closure of stomata and stimulation of continued uptake of water by roots. Osmotic adjustment allows the plant to maintain turgor under decreasing water potential and is a mechanism present to varying degrees among chickpea cultivars (Turner et al. 2001; Toker et al. 2007). Dehydration tolerance allows the metabolism of the plant to continue at low plant water contents (Toker et al. 2007).

1.4 Alleviation of temperature and drought stress

1.4.1 Genetic options

Genetic options for alleviation of constraints to chickpea production have concentrated on developing chickpea varieties that have characteristics to suit different growing environments and maximise grain yields. This included selecting and breeding cultivars of chickpea that: have plant and seed characteristics suited to environments (habit, early vigour, biomass and seed production, seed size and protein content), are resistant to various pests and diseases, overcome
climatic constraints of cold, heat and drought, and have appropriate maturity date for the
growing environment (Singh 1997; Srinivasan et al. 1999; Chaturvedi and Ali 2004; Clarke and
notes that there are 20,000 lines of *Cicer arietinum* in gene banks, and 16,991 recorded at
accessions which covered 13 agronomic traits across geographic regions. From this collection,
a subset of 211 accessions has become a mini-core germplasm collection which has undergone
detailed evaluation (Kashiwagi et al. 2005; Krishnamurthy et al. 2010; Meena et al. 2010). This
mini-core collection has been analysed: (i) to identify the genotypes with high seed yield
potential (traits correlated with high yield potential were plant height, total number of branches,
biological yield and harvest index) (Meena et al. 2010), (ii) for genetic variability of root traits
(Kashiwagi et al. 2005), and (iii) to identify drought tolerant genotypes using a drought
tolerance index (DTI) (Krishnamurthy et al. 2010).

Researchers have been working towards identifying chickpea genotypes which address the
three strategies of drought resistance. Traits which have been found to provide a yield
advantage under drought conditions are extra short duration, large root system, and fewer and
smaller pinnules (Serraj et al. 2003). Traits which have been identified by various authors as
improving tolerance to heat and/or drought stress are: days to first flower and maturity, followed
in order of importance by harvest index, biological yield and pods per plant (Canci and Toker
2009), and pollen viability under heat stress (Devasirvatham et al. 2010).

Plant breeding has developed early maturing chickpea varieties whereby the plant completes
the life cycle before the onset of terminal drought and limiting high temperatures (Kumar and
Abbo 2001; Chaturvedi and Ali 2004). A particular facet of this was the identification of the
gene for early flowering which in combination with early growth vigour can produce relatively
higher yield in short growing seasons (Kumar and van Rheenen 2000). In addition, where a
monsoon rice crop is grown directly before the chickpea crop, short duration rice varieties have
been developed. These rice varieties are harvested earlier (by one month) allowing the chickpea
to be sown earlier, lowering the potential for the chickpea crop to be exposed during the pod-
filling stage to high temperatures and evaporative demand when there is little soil water
available (Johansen et al. 2008b; Joshi et al. 2008). The short duration chickpea varieties mature before terminal drought occurs, and can allow farmers to obtain stable yields (Gaur et al. 2008). However, there can be a yield penalty with short duration varieties of chickpea as it restricts accumulation of biomass which is positively correlated with seed yield in disease-free conditions (Johansen et al. 1997; Serraj et al. 2003; Gaur et al. 2008). Moreover, in short duration varieties, flowering may occur during periods of limiting low temperatures (Croser et al. 2003). Conversely early sowing promotes denser crop canopies that can exacerbate the development of BGM and pod-borer. Hence to overcome the problems of poor biomass, terminal drought, heat stress and forced maturity under late sowing, Chaturvedi and Ali (2004) recommended that genotypes needed to be developed which have early maturity, vigorous seedling growth and cold tolerance during vegetative growth. Such early maturing genotypes with good canopy development have been identified (Chaturvedi and Ali 2004).

Chickpea has deep rooting characteristics whereby it is able to extract water from deep in the soil profile, making it able to survive in water-limited environments and maintain growth during pod-filling (Ali et al. 2005). Root growth of chickpea has been reported to depths of 1.5 m in natural soil profiles (Krishnamurthy et al. 1996). Root biomass, length, density and rooting depth have been identified as traits that assist in avoiding terminal drought (Kashiwagi et al. 2005; Gaur et al. 2008). Serraj et al. (2004) found some recombinant inbred lines which had large root systems and high seed yields, however there was no correlation between the two traits across 257 lines. They recommended that in addition to identifying the molecular markers for root traits, those for biomass and harvest index should also be identified. A chickpea variety (ICC 4958) with a large root system was identified by Saxena et al. (1993): this variety has rapid root growth and can extract water from soil under receding soil water conditions (Krishnamurthy et al. 1996; Serraj et al. 2004). Subsequently, efforts have continued to investigate genetic variability for root traits in the germplasm collections. Examples of work are:

1. Kashiwagi et al. (2005) identified chickpea genotypes from the mini-core germplasm collection which have deep root systems and high root length densities.
2. Ali et al. (2005) found that the root system of ICC 4958 consistently had higher root length density and root dry weight over other genotypes in different growing environments of India and Bangladesh and confirmed ICC 4958 as a potential parent for enhancing drought resistance in chickpea.

3. Gahoonia et al. (2007) identified chickpea genotypes popular in Bangladesh which were found to absorb nutrients in low nutrient soils. These genotypes were better at inducing acidification and had more root hairs than the other chickpea genotypes.

4. Root characteristics and yield of chickpea genotypes under different soil water conditions were examined. Krishnamurthy et al. (1998) determined that the length to weight ratio of roots varied with soil depth and poor soil aeration decreased root length to weight ratios. Kashiwagi et al. (2006) reported that early root growth was positively correlated to seed yield but deep rooting (30 to 60 cm) was correlated with high seed yield in drought conditions.

Plant characteristics which will contribute to higher and more stable yields have been identified for different environments (Gaur et al. 2007). A chickpea ideotype required for tolerance of the abiotic stresses of drought, heat and cold was described by Toker et al. (2007). Characteristics for the ideotype included recommended morphological and physiological traits as well as the traits preferred by farmers. Morphological traits included: crop phenology, plant vigour, flower numbers, leaflet size, root length, and cold tolerance. Physiological traits include an increase in: water use efficiency, stomatal frequency, membrane stability, chlorophyll content, photosynthetic capacity, water potential, transpiration efficiency, turgor capacity, pollen viability, malic acid content, and fertilisation capacity. Farmer requirements included yield improvement, disease and pest resistance, high nitrogen fixation, and seed size specific to either kabuli or desi varieties for a particular growing region. More specifically for the HBT, Johansen et al. (2008b) provided a list of characteristics needed in the HBT, referred to as a farmer-researcher ideotype, as farmers were included in the selection of traits they believed were required in the region (Table 1.5). Many of these identified characteristics overcome the constraints listed in Table 1.3.
Table 1.5. The farmer-researcher ideotype for chickpea improvement in the High Barind Tract (HBT) of Bangladesh as described in Johansen et al. (2008b).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shorter duration chickpea</td>
<td>Escape terminal drought and heat stress.</td>
</tr>
<tr>
<td>Cold tolerance</td>
<td>Allow earlier flowering, pod set and maturity.</td>
</tr>
<tr>
<td>Improved seedling establishment</td>
<td>Specifically to combat the low soil water contents at sowing.</td>
</tr>
<tr>
<td>Deep rooting</td>
<td>Chickpea plant can obtain residual soil water from deeper in the soil profile.</td>
</tr>
<tr>
<td>Improved resistance to insects and disease</td>
<td><em>Helicoverpa</em> pod-borer, Collar rot, fusarium wilt.</td>
</tr>
<tr>
<td>Seed characteristics</td>
<td>To resemble the old variety of Nabin, also called Bari Chola 1, which has a high consumer preference.</td>
</tr>
</tbody>
</table>

1.4.2 Agronomic options

1.4.2.1 Crop establishment

On-farm seed priming is a technology which has been found to improve the rate of germination and emergence as well as increase seedling vigour, advance crop development, increase yield and reduce damage caused by disease (Musa et al. 2001; Murungu et al. 2004; Rashid et al. 2004; Harris et al. 2005). Seed priming involves soaking seed in water (about 8 hours for chickpea), followed by a period of drying before sowing (Musa et al. 2001; Harris et al. 2005). The seed is then sown in a hydrated state, preceding radicle emergence (Murungu et al. 2004; Ghassemi-Golezani 2010). A study on chickpea germination alone found that priming did not improve germination percentage but that germination rate and uniformity in germination time was improved (Elkoca et al. 2007). The benefits of seed priming are attributed to the improved rate of germination and emergence of seedlings in the soil. Where primed and not primed seedlings were found to emerge on the same day, there was no advantage in priming (Murungu et al. 2004). In a drying seed-bed, where soil physical conditions may become limiting to emergence due to increased soil strength, the primed seed may have an advantage in that it can emerge more rapidly before conditions become limiting (Murungu et al. 2004). However, regardless of whether a seed is primed or not primed when a seedling attempts to emerge through a seed-bed of high strength it may fail or be damaged.
The detrimental effects on seed germination and seedling emergence due to low soil water content, large aggregate size and poor seed-soil contact may also be mitigated by seed priming (Murungu et al. 2003). Instances where priming did not improve seed germination or seedling emergence were attributed to either seed-beds which were non-limiting to emergence, or where soil physical properties limited both the primed and non-primed seed. Additional studies of on-farm seed priming have found decreased incidence of symptoms and damage from some virus infections and disease and improved nodulation (Musa et al. 2001; Harris et al. 2005). Where availability of the micronutrient Mo is limited in the soil, small amounts delivered with *Rhizobium* via seed priming has been found to be easy to apply and cost effective, and has resulted in improved nodulation and grain yield (Johansen et al. 2007).

With on-farm seed priming there have been reports of: reduced damage from collar rot in chickpea (caused by the fungus *Sclerotium rolfsi*) (Musa et al. 2001), reduced severity of mungbean yellow mosaic virus infection in mungbean (Rashid et al. 2004), and reduced incidence of downy mildew in pearl millet (*Pennisetum glaucum* L.) (Harris et al. 2005). The benefits of priming which are associated with increased resistance to disease were hypothesised to be due to increased vigour of the plant (health), faster development of the plant (escape) or through the responses invoked in the seed under conditions of rapid imbibition which allow the seedlings to have continued resistance to stress (Systemic Acquired Resistance, SAR) (Rashid et al. 2004). In the HBT across two seasons (with and without in-season rainfall), seed priming increased grain yield by 17% in on-farm demonstrations and 20 to 47% in farmer paired-plot trials (Musa et al. 2001). Plant population and early seedling growth was improved with priming, however, the number of pods per plant and 1000 grain weight were not. On-farm participatory trials in India and Bangladesh have resulted in farmers adopting the practice in wheat, linseed, chickpea, upland rice and maize (*Zea mays* L.) (Harris et al. 1999; Musa et al. 2001; Salam et al. 2008). Farmers’ perceptions were that on-farm seed priming: (i) improved the rate of emergence, (ii) allowed planting in drying soils, (iii) required less re-sowing of areas which failed to emerge, and therefore saved money, (iv) improved competition with weeds, (v) caused faster growth and earlier maturity, and (vi) improved yield (Clark et al. 2003b). Seed
priming has been identified as a technology easily implemented, with low risk and clear benefits
(Murungu et al. 2004; Harris et al. 2005).

1.4.2.2 Plant population density, row spacing, and drought

Both intermittent and terminal droughts have been identified as constraints to the production of chickpea in both the HBT of Bangladesh and the south-west of WA (Table 1.4). Of the three strategies that can allow chickpea plants to adapt to drought conditions (drought escape, drought avoidance and drought tolerance) (Thomson et al. 1997; Toker et al. 2007), drought escape and avoidance mechanisms offer most scope in both the HBT of Bangladesh and south-west WA. These are the strategies which aid the plant to avoid drought by maximising overall water uptake during the crop growth cycle, but often centre on crop management strategies which conserve soil water and/or match crop phenology to available soil water. These can be implemented through early sowing, cultivar selection, mulching, tillage type, fallowing and through modification of the plant population density (Katyal and Vittal 2003; Mohapatra et al. 2003; Turner 2004). Of the above management strategies, investigation of the plant population density (PPD) is particularly relevant to the HBT of Bangladesh, since minimum tillage techniques are currently being implemented and recommendations of plant arrangement within-rows and between-rows in this new system still need to be defined. In south-west Australia, the discussion of PPD is still relevant for chickpea and other crops as research has identified that grain yields can vary depending on row spacing and seasonal rainfall (Riethmuller and MacLeod 2000, 2001, 2002). The disadvantages and seasonal risks of wide row spacing in terms of grain yields need to be determined as the continued adoption of minimum tillage and conservation tillage in these environments has implications for pest and disease and management which may benefit from wide rows and weed management which can be controlled by selective herbicides and physical control methods (Peltzer et al. 2009).

Over a range of PPD, the overall grain yield can be relatively stable per unit area, because the grain yield per plant increases with decreasing plant population density (Saxena 1980a; Siddique et al. 1984; Valimohammadi et al. 2007). Other researchers report that when the PPD is increased, chickpea seed yields can also increase (Jettner et al. 1999; Liu et al. 2003; Khan et
Grain yields, above-ground biomass, harvest index, branch size, seed size, and pods per plant have also been found to vary with changes in PPD (Siddique et al. 1984; Beech and Leach 1989b; McKenzie and Hill 1995; Jettner et al. 1999; Liu et al. 2003; Valimohammadi et al. 2007; Khan et al. 2010). These differences can be attributed to morphological plasticity of the chickpea plant which allows the plant to compensate for lower plant numbers through better growth of the remaining plants (Saxena 1979). The ability of the chickpea plant to minimise fluctuation in grain yield with plant numbers has been attributed to: (i) variations in branch numbers (Saxena and Sheldrake 1980) and rate of branch development (Siddique et al. 1984), (ii) the greater contribution of grain yield and higher pod numbers to the main stem than side branches at higher PPD (Siddique et al. 1984), and (iii) changes in pod distribution per plant whereby there are fewer pods per plant at high PPD, but more pods per unit area (Jettner et al. 1999; Regan et al. 2003). These characteristics have also been shown by other researchers to increase seed yield when chickpea was sown at high PPD (Beech and Leach 1989b; Jettner et al. 1999; Liu et al. 2003). Grain numbers per pod have been reported to decrease with greater seed rates (Khan et al. 2010) but grain numbers per pod have been reported to be quite stable under varied PPD or seed rate (Siddique et al. 1984; Jettner et al. 1999; Regan et al. 2003). By contrast, grain weight has not shown a consistent response to seed rate and/or PPD: no change in grain weight has been reported for kabuli and desi types (Liu et al. 2003; Regan et al. 2003), increases in grain weight have been reported at lower seed rates for kabuli types (Yau 2005), and decreased grain weights have been reported with high seed rates and PPD, respectively, in desi types (Jettner et al. 1999; Khan et al. 2010).

Saxena (1980a) commented that under limiting environmental conditions during vegetative and reproductive growth, response of chickpea to differences in PPD will depend on available soil water content. Increased PPD has high yield potential as there will be early canopy cover, which allows greater interception of light and increased photosynthesis (McKenzie and Hill 1995; Liu et al. 2003). However, at high populations the plant-to-plant competition is high which leads to competition for water and nutrients. In a water-limited environment (low potential yield), high plant populations are of no benefit (Siddique et al. 1984; Jettner et al. 1999). Higher plant populations are recommended in Mediterranean-type environments which
have within growing season rainfall compared to locations which rely on stored soil water for crop growth such as the summer-dominant rainfall environments (Turner 2004). The reported PPD to obtain optimum yield varies depending on climate and region (semi-arid, Mediterranean, sub-tropical). Jettner et al. (1999) reported that at high PPD, chickpea seed yield was not affected by inter-plant competition where rainfall was not limiting growth. In south-west WA when yield potential is predicted to be greater than 1.5 t/ha, the recommended plant density was 70 plants/m² to obtain optimum seed yields (Jettner et al. 1999). However, at lower yield potentials of about 1 t/ha, 50 plants/m² was recommended (Jettner et al. 1999). Across south-west WA, the highest grain yields were found at PPD between 30 and 89 plants/m², within the range of PPD tested which was 11 to 96 plants/m² (Jettner et al. 1999). In other Mediterranean-type environments, optimum PPD was reported as 25 plants/m² in non-irrigated conditions, and 50 plants/m² with irrigation (in Iran; Saxena 1980a). Winter sowing (December) and a PPD of 28 plants/m² achieved better yields compared to March sowing and PPDs of 19 to 28 plants/m² (in Israel and Syria; Saxena 1980a). The recommended PPD for chickpea in southern Queensland was variously reported as 40 plants/m² (Beech and Leach 1989b), or 20 to 45 plants/m² (Brinsmead et al. 1996) while 25 to 30 plants/m² was recommended in the northern regions (Gentry 2010). In the summer-dominant rainfall environments where chickpea is winter sown, changes in PPD had little effect on seed yield over a range of PPDs although the PPD recommended was 33 plants/m² in India (Saxena 1980a). Grain yield of crops can plateau with increasing PPD, whereby there is no further advantage to increased plant density (Peltzer et al. 2009). The above recommended PPDs have been suggested based on such yield plateaus (Beech and Leach 1989b, 1989a; Khan et al. 2010) and also based on economic optimum plant density (Jettner et al. 1999).

The benefit of sowing into wide or narrow rows in drought-prone environments has been investigated for a range of crops (sorghum (Sorghum bicolor L. Moench), wheat, lentil, lupin and chickpea) in a range of environments (Beech and Leach 1988, 1989a, 1989b; Riethmuller and MacLeod 2000, 2001, 2002; Whish et al. 2002; Whish et al. 2005; Kleemann and Gill 2010a). Investigations have studied the benefit of wide row spacing either to overall
management of the crop and environment or to crop yields. For the chickpea cropping system, these investigations have concentrated on the concepts of:

1. maintaining a minimum tillage system which retains crop residue on the soil surface to decrease soil surface erosion and controls weeds (Felton et al. 1996);
2. sowing to obtain a plant density, based on row spacing and intra-row spacing, where yields are not affected by competition to the crop for water and nutrients by weeds (Whish et al. 2002);
3. reducing the incidence of fungal disease such as BGM as wider row spacing delays canopy closure to later in the season when the conditions for BGM infection are less favourable and allow for better ventilation and drying in the crop canopy (Siddique et al. 2000; Riethmuller and MacLeod 2001);
4. partitioning plant access to water and nutrients in the soil profile by sowing plants in wider rows, which means root growth during the season allows access to water within the row at important crop growth stages (Beech and Leach 1989b); and
5. combining row spacing and intra-row spacing to determine which plant density and configuration improves plant yield (Beech and Leach 1988).

Agronomic crop management guidelines across Australia promote production of crops (cereal and broadleaf) at wider row spacings (>0.18 m to 1 m). Benefits cited are: ease of planting into stubble to maintain zero tillage systems, improved disease and weed management, improved water use efficiency, decreased input costs as band spraying to control disease can occur over crop rows only, lower humidity levels that reduce the incidence of foliar fungal diseases, and use of inter-row cultivation to control weeds as outlined above (Gentry 2010; Martin et al. 2010). Plants sown at wide row spacing have the same plant density per unit area as plants sown at narrower spacings. At wide row spacings, there is greater competition between plants within the row for early access to resources (water/nutrients). This can decrease the early biomass production of individual plants, leave water between the rows for later crop use and in turn decrease the potential for water stress at grain filling (French and Wahlsten 2003; Whish et al. 2005; French and Harries 2006). In addition, wide row spacing is often promoted as yielding better than narrow rows in conditions of moisture stress (often described
as conditions of low yield potential) but not promoted in seasons of minimal water stress (high yielding potential conditions) (Gentry 2010). However, this recommendation of row spacing based on growing season rainfall, stored soil water and yield potential (Whish et al. 2005) does not always hold true, and can differ according to the genotype, plant density, location, and crop being investigated (Beech and Leach 1988; Whish et al. 2002; Kleemann and Gill 2010b).

Conventional row spacing for chickpea is between 18 and 35 cm in south-west WA (Thomson et al. 1997; Jettner et al. 1999; Siddique et al. 2001; Knights and Siddique 2002; Harries et al. 2005b), but wider row spacings to 1 m have been reported (Riethmuller and MacLeod 2002). In the literature, the conclusion as to whether there are yield benefits to sowing chickpea into wide rows is often related to pre-season and in-season rainfall, which determines if the crop will have high or low yield potential (Brinsmead et al. 1996; Felton et al. 1996; Whish et al. 2005). In a season with low yield potential (water-limited conditions), wide row spacing can have no effect on chickpea yields (Beech and Leach 1989b; Felton et al. 1996). However, in high yielding (non water-limiting condition) situations wide row spacings have reduced seed yield (Brinsmead et al. 1996; Felton et al. 1996; Riethmuller and MacLeod 2002; Whish et al. 2002).

In seasons of low yield potential, chickpea crops have been found to have no yield disadvantage when grown in wider rows (row spacing 25 to 100 cm in northern NSW; Felton et al. 1996, row spacing 18 to 72 cm in southern Queensland; Beech and Leach 1989b; Brinsmead et al. 1996). Whilst at high yield potentials wide row chickpea crops have been found to have decreased yields (row spacing 25 to 100 cm in northern NSW; Felton et al. 1996; Whish et al. 2002). Others reported decreased crop biomass within the season with increased row spacing but no yield decline (Beech and Leach 1988). These results are in regions of summer-dominant rainfall growing on soils which have potentially high profile soil water content at sowing (Riethmuller and MacLeod 2002; Berger and Turner 2007; Kleemann and Gill 2010b). In south-west WA, the Mediterranean-type environment with winter-dominant rainfall, where soil water was not limiting within the season the wider rows of 95 cm had a decline in yield, from the narrower row spacing of 38 cm, no other row spacing treatments (19 to 76 cm) had yield differences (Riethmuller and MacLeod 2002). In dry growing season conditions, with low yield
potential, yields were lower in narrow rows of 19 cm whilst in another experiment there was no yield decline across row spacing treatments of 19 to 76 cm (Riethmuller and MacLeod 2001). These results are similar to those reported for lupins in south-west WA, whereby wider rows gave better yields than narrow rows in dry seasons, and a yield disadvantage in high yield potential conditions (Crabtree et al. 2002; French and Harries 2006). Within south-west WA, there are two distinct zones, the northern agricultural region which has warmer winters and the southern agricultural region where winters are colder and longer (Harries and French 2008). Harries and French (2008) suggest wide rows may be used for lupin production in the northern region whilst in the southern region narrower row spacings would be more suitable. This recommendation would be a means of managing the water resources to be available for grain fill at the end of the growing season and would be pertinent for other crops grown within the region such as chickpea.

In summer-dominant rainfall environments where chickpea is winter sown, similar variable results have also been found with interactions between row spacing and with growing season rainfall. In India, increasing row spacing from 17.5 to 30 cm (PPD 33 plants/m²) increased seed yield (Saxena and Sheldrake 1974). In Pakistan, chickpea sown at row spacings of 30 cm had greater grain yield than 50 and 100 cm row spacing with both 190 mm and 93 mm of growing season rainfall (unknown PPD) (Khan et al. 2001). In a range of row spacings from 15 to 45 cm (constant PPD), the wider row spacing had the better seed yield in seasons with 132 mm and 28 mm of growing season rainfall (Khan et al. 2010).

In some cases, widening rows to a certain level such as 25 to 50 cm, achieves no yield decline and there will often be a plateau in yield, however at the widest spacing of 100 cm a yield decline occurs (Riethmuller and MacLeod 2002; French and Wahlsten 2003; Peltzer et al. 2009). This can give an indication of the maximum row width (at constant PPD) before a decline in yield occurs (Peltzer et al. 2009). The resultant plateau in seed yield is due to a decline in flowers per plant with the increase in plant numbers (Peltzer et al. 2009). Defining the threshold PPDs associated with yield plateaus under varied row spacing can be integrated into overall crop management strategies for weed, pest and disease control.
Any modification of PPD within and between-rows needs to consider the response of foliar
diseases to changes in plant density and canopy configuration. Botrytis Grey Mould is sporadic
in the HBT and Ascochyta blight is a severe disease in south-west WA. These foliar diseases
can severely reduce yield if not managed (Singh et al. 2007; Bretag et al. 2008; Johansen et al.
2008a). In both locations when temperatures during the growing season are optimum for the
diseases, chickpea crops can have a closed canopy which creates higher humidity and promotes
infection (Fleet et al. 2004; Johansen et al. 2008a; Salam et al. 2011). A high PPD thus favours
the development of foliar disease. However, provided the canopy remains disease-free yield
potential is increased with increasing PPD. When wider row spacings are implemented, the
crop canopy may remain open for longer, obviating the conditions which promote foliar
diseases (Siddique et al. 2000; Riethmuller and MacLeod 2001).

1.4.2.3 Cultivation practices

Tillage of the soil refers to the preparation of the soil seed-bed for subsequent sowing of
seed and placement of fertiliser. Tillage is the main method to control weeds but other
advantages of tillage are the incorporation of plant residues and breaking of soil surface and
hardpans and increasing surface roughness which can assist in the infiltration of water
(Schjonning and Rasmussen 2000; Mohanty et al. 2006). Loosening soil below the seed can
decrease soil strength and increase rooting density below the seed, improving shoot growth and
grain yields (Schmidt et al. 1994). Tillage is used to ensure the seed-bed is of an appropriate
tilth, to allow improved seed-soil contact and cover the seed with soil, allow water and air
movement and unimpeded root growth (Tapela and Colvin 2002).

Since the 1970’s, in world agriculture generally there has been a move away from full
tillage to reduced or minimum tillage (Derpsch et al. 2010). In a minimum tillage system, only
soil in a narrow furrow is disturbed for seed (and fertiliser) placement. However, all machinery
must operate through plant residues and weed control must be by herbicides or other integrated
management methods. Baker and Saxton (2007) listed 26 advantages to moving from full
tillage to no-tillage that centre round improvements to soil structure, soil water characteristics,
soil nutrient status as well as economic savings. The type and magnitude of the benefits will
depend on the level to which tillage is reduced. Of the disadvantages listed for no-tillage, many centred on the changes required to the agricultural system for weed control, additional equipment requirements, and changes to crop agronomy and nutrient cycling (Baker and Saxton 2007).

The level of disturbance of the surface soil decreases with the change in tillage techniques from full tillage through to forms of strip tillage (where only a furrow is cultivated) and then to zero tillage (where there is no-tillage, just a tine pushed through the soil). The soil physical properties of bulk density, soil strength, aggregate mean weight diameter and surface roughness will vary with tillage type (Barzegar et al. 2003). The inclusion of residue retention in the system will also modify the soil properties through stabilization of soil structure. With tillage the proportion of loose soil may increase, increasing soil porosity and allowing infiltration of water and decreased runoff (Mamkagh 2009). However, less cultivation and compaction can improve aggregate stability and improve soil water holding capacity over time by increasing the proportion of mesopores relative to macropores (Tisdall and Oades 2003).

Of the constraints listed in Table 1.3, eight can be alleviated by agronomic solutions and of those at least five would benefit from alternative tillage techniques. Changes to the tillage technique used could benefit the production of chickpea in the HBT through: modification of the seed-bed, timely sowing, placement of seed and fertiliser into moist soil, decreased labour requirements, and overall cost savings (Reicosky and Saxton 2007; Johansen et al. 2012).

One of the main identified constraints to chickpea production in the HBT of Bangladesh is the drying of the surface soil after rice harvest before the chickpea crop can be planted, leading to poor crop establishment. This is a consequence of the time it takes for a farmer to harvest and handle the previous rice crop, which is a priority, and the traditional broadcast method of sowing the rabi season crop which required multiple tillage passes to create the seed-bed (Hobbs et al. 1997; Musa et al. 2001; Kumar et al. 2007; Johansen et al. 2008a). The delay in planting the chickpea crop has two consequences (i) the surface soil dries to below optimum for seedling germination and emergence, and (ii) the chickpea crop is sown late, so that crop emergence may be limited by low temperatures and later in the season grain filling is limited by high temperatures. In addition, limited rainfall and low-quality seed can also contribute to poor
establishment (Harris et al. 2005). The development of mechanised row-sowing by the SPST as described earlier in Section 1.2.2.1 enables the chickpea and other post-rice, rabi season crops to be sown into narrow furrows seeded during one-pass. Further development of the planter, enabled delivery of both seed and fertiliser (Bell et al. 2012). In one-pass of the SPST, the entire surface layer of soil is cultivated, the seed and fertiliser are placed in furrows, followed by levelling of the soil surface with a roller. The original 2WT with planters (PTOS or SPST) enabled the placement of the seeds into rows but still disturbed the entire soil surface of the field (Johansen et al. 2012). Single pass shallow tillage is considered to be reduced tillage (Johansen et al. 2012). Minimum tillage planting is an alternative to full cultivation (Haque et al. 2004). With the shift to minimum tillage there is also the need for planting machinery that can sow through retained rice stubble, and plant with minimal disturbance of the surface soil. The SPST was further developed for minimum and zero tillage options by removing rotary blades from in front of the tine. When rotary blades were retained only in front of the tine this was considered ST and when all rotary blades were removed it was considered ZT (Roy et al. 2009; Johansen et al. 2012). Benefits of these tillage types are the shorter time required for preparing and sowing each field; more fields can be sown during the optimum sowing window and fertiliser can also be placed in rows in close proximity to the seed. The time saving in sowing wheat after rice with zero tillage is 10 to 15 days compared to a conventionally sown crop (Haque et al. 2004).

The original planters were set to one specific tillage type and could not be modified. Further development of the technology produced the Versatile Multi-crop planter (VMP) which allowed changes to the configuration of one planter to be either SPST, ST, or ZT. The VMP has been through several iterations to develop capabilities which allow full rotary tillage through to ZT, and is described in Table 1.6. As the numbers of rotary blades in front of the tines are reduced, the amount of cultivation of the soil is decreased. The number of tilling operations are also reduced with a move to minimum tillage planting. Current land preparation and sowing for rabi season crops can require two to eight tilling operations, or machine passes (Wohab et al. 2006).
Table 1.6. The configuration of the Versatile Multi-crop Planter when sowing by zero tillage, strip tillage or by full tillage with one or more passes.

<table>
<thead>
<tr>
<th>Level of surface disturbance</th>
<th>Tillage type</th>
<th>Rotary blades</th>
<th>Seed and fertiliser delivery</th>
<th>Furrow or seed covering</th>
<th>Total number of passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-tillage</td>
<td>Zero</td>
<td>0</td>
<td>Tine$^1$</td>
<td>Roller or press wheel</td>
<td>1</td>
</tr>
<tr>
<td>Minimum tillage</td>
<td>Strip</td>
<td>4 in front of each furrow opener</td>
<td>Tine</td>
<td>Roller or press wheel</td>
<td>1</td>
</tr>
<tr>
<td>Full tillage</td>
<td>Single pass shallow tillage (SPST)</td>
<td>28 across entire rotating shaft</td>
<td>Tine</td>
<td>Roller or press wheel</td>
<td>1</td>
</tr>
<tr>
<td>Full tillage - multiple pass</td>
<td>Broadcast</td>
<td>Full tillage</td>
<td>Broadcast</td>
<td>Full tillage</td>
<td>2 or more</td>
</tr>
</tbody>
</table>

$^1$Tine can also be referred to as a furrow opener

The tillage type used, full tillage to ZT can be modified to suit the conditions at sowing. When required this can allow tillage to greater depth to break a hard pan, sowing seed deeper into moist soil and modifying the tillage type to ensure adequate soil tilth for seed-soil contact and furrow covering (Haque et al. 2010). The size and shape of the furrow and layer of soil covering the seed have also been found to control vapour loss from the furrow, which can be important in drying soils (Choudhary and Baker 1982; Baker 2007b). Haque et al. (2010) made recommendations for operation of the VMP in Bangladesh in wet soil or dry soil conditions. In soils which dry quickly and have hard pans the furrow should be deep and wide: where the soil is wet, the seed placement can be shallow (Haque et al. 2010). In heavy, hard setting soils, ZT requires greater traction than possible with the 2WT, so ST is preferred (Haque et al. 2010). The amount of seed and fertiliser required for adequate plant numbers in the field is decreased with mechanised row-sowing, therefore the costs to farmers is not as prohibitive and the move to one-pass sowing frees up labour (Baker and Saxton 2007; Johansen et al. 2012). Relative cost savings when ZT was implemented were 83 % for wheat and 89 % for maize (Haque et al. 2004). When SPST was compared to ST, fuel consumption was 20 % less and the cost of planting 8 % less (Justice et al. 2004). In another report, across the range of minimum tillage techniques there were fuel savings of 38 to 82 % and operational costs reduced by 23 to 52 % compared to full tillage (Haque et al. 2011).
The VMP has since been developed to sow multiple crops in any of the modes described in Table 1.6. The VMP can be modified in the field to add or remove rotary blades and furrow openers to suit the crop sown, or the soil conditions at sowing (Haque et al. 2011). Testing of the seeders for sowing chickpea, black gram (Vigna mungo L. Hepper), mungbean, wheat, maize, and rice has occurred in research trials and farmers’ fields across Bangladesh (Islam et al. 2010; Haque et al. 2011; Islam et al. 2011a; Islam et al. 2011b; Islam et al. 2011c). The planter has also been developed for maintaining and planting on permanent bed systems including minimal reforming of the beds between crops (Haque et al. 2011). Where rice is direct-seeded rather than transplanted, earlier seeding of the next rabi season crop is possible (Saleh and Bhuiyan 1995). For chickpea and lentil, research has also tested seeding rate, fertiliser rate and location and to a lesser extent seeding depth with the VMP (Kabir et al. 2010; Bell et al. 2012). Other research will determine if there are benefits to soil structure and organic matter accumulation from using minimum tillage during the rabi season crop, even if the rice crop still requires substantial disturbance of the soil. The move towards minimum tillage will also allow the practice of conservation agriculture, which applies three principles of crop management: (i) continuous minimum soil disturbance, (ii) retention of crop residue to allow a permanent organic cover, and (iii) a diversification of crop rotations (Derpsch et al. 2010). In a system with rice, where conventional methods of sowing have required puddling the soil, the soil loses aggregate stability, porosity and structure (Hobbs et al. 1997). Direct seeding of rice will be required to maintain the first principle of conservation agriculture, minimum soil disturbance. The retention of crop residues as mulch and surface cover, the second principal of conservation agriculture is further limited by the alternative uses of crop residues in developing countries such as Bangladesh for animal feed and fodder (Lal 2007).
1.5 Objectives

Water and temperature stress are abiotic constraints to chickpea growth which apply in both regions targeted in this thesis, south-west WA and the HBT. Chickpea growth and yield formation are directly affected by high or low temperatures that exacerbate crop stress where available soil water is unable to meet plant demand. In both regions, water and temperature stress lead to similar problems of poor crop establishment, reduced crop growth rates, and to both intermittent and terminal drought. These water and temperature stresses are likely to be exacerbated by ongoing climate change due to increased temperatures and decreased rainfall (Climate Commission 2011). Further research to maximise water use efficiency is required in WA to alleviate these constraints for the production of chickpea. In the HBT, the recent changes from broadcast-sowing to mechanised row-sowing may alleviate, or alternatively worsen, these constraints. This thesis examines some agronomic options for alleviating water and temperature constraints that limit chickpea growth.

In soil profiles where moisture may become limiting at any time during the growing season, manipulation of within-row and between-row plant spacing can modify plant access to available water and thereby affect yield. This thesis examines the interactions of PPD, crop row spacing and initial soil water content on chickpea growth and yield in addition to the effects of in-season rainfall. This is relevant in both regions, in south-west WA where the soil profile usually has low water content at sowing and the crop relies on within-season rainfall, and in the HBT where there is high soil water content in the soil profile at sowing but limited in-season rainfall.

Poor crop establishment is an issue in both regions. In south-west WA, rainfall is the main driver of successful establishment, and as such adequate break-of-season rainfall and timely sowing are the main requirements. In the HBT of Bangladesh, in addition to timely sowing after rice harvest, the shift to mechanised row-sowing requires further research to define conditions required for successful chickpea establishment. Determination of the soil physical conditions which limit chickpea establishment will define the range of conditions which are optimum for chickpea establishment; furthermore, the influence of tillage type on optimum soil physical conditions for sowing needs to be established.
Temperature stress includes either high or low temperatures that hinder chickpea development. High temperatures are commonly coupled with terminal drought conditions as mentioned above, and they shorten the duration of each growth stage (emergence, vegetative, reproductive). Low temperatures can limit the vegetative growth of chickpea, the development of flowers and pods and increase the duration of crop growth stages. Agronomic solutions to avoiding temperature stresses in both regions include timely sowing, but there is still a need for better definition of the periods when exposure to adverse temperatures most limit chickpea growth.

Objectives of the study are to:

1. Determine effects of initial profile soil water content and row spacing configuration on chickpea water use, growth and yield (Chapter 2).

2. Define the limits of soil water, soil aeration and soil strength required by chickpea for germination and establishment (Chapter 3).

3. Define the soil physical conditions at sowing in the HBT with the different tillage configurations and determine if conditions (i) meet the requirements for chickpea germination and establishment determined in objective 2, and (ii) meet the requirements for timely early sowing and rapid vigorous seedling growth of chickpea (Chapters 4 and 5).

4. Define for both target regions when temperature and soil water conditions are likely to limit chickpea growth, and the extent of yield decline associated with sub-optimal conditions (Chapters 2, 4 and 5).

5. In the HBT identify the optimum sowing window which will both allow successful crop establishment and limit exposure of chickpea to adverse conditions during the growing season (Chapters 4 and 5).
2 The effect of row spacing and growing season rainfall on chickpea yield and water use

2.1 Introduction

Drought has been identified as the most important abiotic stress to chickpea (Toker et al. 2007) as it occurs in most chickpea-growing regions (Berger and Turner 2007). In a crop that is entirely rainfed, drought may occur at any time during the growing season. However, chickpea is most sensitive to drought at the flowering and podding stages (Khanna-Chopra and Sinha 1987). In chickpea growing environments, terminal drought occurs when soil water content in the profile has been depleted which coincides with the time of pod set and seed development. In the Mediterranean-type environment of south-west WA the chickpea crop relies solely on growing season rainfall for crop production, between 209 to 438 mm (Siddique et al. 1999).

Production of chickpea in drought-prone environments has been improved through plant breeding and crop management (Mohapatra et al. 2003). Management of crop agronomy to alleviate terminal drought includes early sowing, use of short season cultivars, seed priming, weed management, fertiliser management, minimum tillage, mulching, fallowing, and optimising plant population (Katyal and Vittal 2003; Mohapatra et al. 2003; Turner 2004; Harris et al. 2005). Crop management techniques either improve storage of water in the soil profile or alter the way plant roots access water in the soil profile, the aim being to optimise the timing of water extraction from the soil profile by the crop. Altering the plant population density (PPD) and row spacing (RS) may be a means of utilising the morphological plasticity of chickpea to achieve high yields. Morphological plasticity in chickpea allows the plants to modify the production of biomass and yield components depending on PPD (Saxena 1979). Siddique et al. (1984) found that individual chickpea plants sown at lower PPD had greater uniformity in branch size and seed weight than plants sown at higher PPD, this allowed plants sown at lower PPD to compensate for less plant numbers. By contrast, as PPD increased there was an increase in above-ground biomass but lower harvest index per plant.

Plant population density, and plant arrangement within-rows and between-rows, can affect the timing of drought in the crop within the growing season and ultimately determine final
yields. Lower plant densities are preferred in the summer-dominant rainfall environments which rely on stored soil water compared to the Mediterranean-type environments which rely on growing season rainfall (Turner 2004). Chickpea grain yields can have a positive relationship with PPD until a plateau is reached and a further increase in PPD has no yield advantage (Beech and Leach 1989b, 1989a; Jettner et al. 1999; Liu et al. 2003). When growing season rainfall, soil water storage and plant available water are not limiting then there is high yield potential: when all or some of these factors are low, yield potential is low (Whish et al. 2005).

Decreasing the PPD with lower seed rate can control the biomass production early in the season, to benefit final grain yields (Yau 2005). A lower PPD, in a low yield potential season may allow water to be conserved for use by plants later in the season, whereas high plant density will deplete the available water earlier (Jettner et al. 1999). Modifying the plant configurations, through row spacing can also modify the uptake of water and nutrients by the crop throughout the growing season. In modifying the row spacing at the optimum PPD it is the inter-row spacing and the intra-row spacing between plants which changes, altering the planting configuration. With this rationale, at wider row spacing the plant density per unit area is the same as in narrower row spacing. In wide rows the competition between plants for resources (water/nutrients) early in crop production is greater within the seed row and resources remain between the rows for use later in the season (Whish et al. 2005). As row spacing is widened increased early competition for water and nutrients and less interception of solar radiation by the crop can lead to decreased biomass production early in the season (French and Harries 2006). Any reduction in early plant growth due to within-row competition will restrict root growth and may limit later access to between-row water and nutrients. Provided there is limited restriction to root growth at wide row spacing, the plant will access soil water stored in the middle of the row later in the growing season during crop growth stages when it will be most beneficial for yield formation under terminal drought (French and Wahlsten 2003; Whish et al. 2005). The allocation of water use to later in the season can decrease water stress at grain filling which is indicated by high harvest index (French and Harries 2006). Regardless of the row spacing implemented, the onset of crop water stress at grain filling can cause lower grain yields (Riethmuller and MacLeod 2002). However, previous studies in Australia of row spacing have
included no detailed measurement of soil water storage or crop water use to verify the pattern of allocation of water use by the crop within a season.

Recommendations of PPD and row spacing are made based on the assumed yield potential of the season. In the Mediterranean-type environment, in rainfed conditions where soil water may become limiting, the optimum PPD was less at low potential yields than at high potential yields (Jettner et al. 1999). Recommended PPD will also change with location. For example in south-west WA, the recommended plant population is 50 plants/m² at low yield potential and 70 plants/m² at high yield potential whereas in southern Queensland the recommended density is 40 plants/m² (Beech and Leach 1989b; Jettner et al. 1999). Recommendations for row spacing in southern Queensland differentiate between wide rows (50 to 100 cm) or narrow rows (15 to 40 cm) depending on yield potential, planting equipment and other management constraints (Gentry 2010). The current recommendation in south-west WA is for chickpea to be sown at a row spacing of 25 cm, to achieve a PPD of 40 to 45 plants/m² (Harries et al. 2005b).

In the Mediterranean-type environment of south-west WA, research suggests that for a constant PPD the yield potential of the growing season will determine the optimum row spacing for chickpea which in turn may be based on seasonal climate forecasts (Whish et al. 2005). When the amount of pre-season rainfall is considered this additional profile soil water may benefit crop growth and may also influence the choice of row spacing.

This chapter examines the water use and plant growth of chickpea plants in different row spacing treatments at constant PPD under different initial soil water conditions. Row spacing treatments were chosen to represent the narrow row spacing currently recommended in south-west WA (Harries et al. 2005b), to wider row spacing of 100 cm which has been found to improve grain yields of lupins in south-west WA (French and Harries 2006). The treatments were chosen to determine if chickpea plants grown at >23 cm row spacing had improved grain yield under water deficit. Previous research into row spacing configurations in chickpea have not looked at the effect of different starting soil water scenarios on chickpea growth and yield. These experiments were only completed in south-west WA and the aim was to determine if summer rainfall (November to March) in south-west WA will improve yields of chickpea sown in winter (June).
Soil profiles with two different soil water contents were created through pre-sowing irrigation to investigate the effects of initial soil water content and row spacing on chickpea growth and yield. Soil water content and chickpea plant growth were examined to:

1. Determine the effect that row spacing configurations and different initial profile soil water levels have on chickpea growth and yield.
2. Determine if different row spacing configurations alter the extraction soil water by the crops through the growing season.
3. Determine if the seasonal patterns of soil water extraction explain any growth and yield differences found.

2.2 Materials and Methods

Experiments were conducted at Merredin, Western Australia (31.50°S, 118.22°E), from June to December in 2007 and 2008, on a Calcic Red Dermosol (Isbell 1996). In 2007, treatments included row spacing (RS), pre-season irrigation, fertiliser placement and seed priming at sowing. The fertiliser treatments in 2007 were to test whether the concentration of fertiliser under very wide rows caused any toxicity to the crop, whilst the addition of seed priming was to test if crop establishment could be improved. This chapter concentrates on plant growth and water use, therefore the treatments of fertiliser placement and seed priming in the 2007 trial will not be discussed in this thesis but are reported in French and Vance (2008). In 2008, treatments included row spacing and pre-season irrigation. Whilst both experiments had similar measurements taken within the season for plant growth parameters, the 2008 experiment had greater emphasis on soil water content and plant water stress.

The pre-season irrigation was applied to fill the soil profile (to about 50 cm depth) to field capacity, simulating summer fallow rainfall events. In addition the amount of water added as irrigation was similar to that of the mean rainfall (73 mm) which falls from January to March in Merredin (1903 to 2013 records) (BOM 2013). Irrigation was applied by tractor mounted sprinkler, tractor speed 5 km/h. To ensure runoff was minimised and the field was not damaged by the tractor crossing the field the irrigation days were split by periods of no irrigation. Irrigation was stopped when it was deemed field capacity had been reached.
Chickpea cv. Genesis 836 (100 seed weight, 18.75 g) was sown at 110 kg/ha for all row spacings on 26 June 2007 and 19 June 2008. Double superphosphate (17.7 % P, 3.6 % S, 16.2 % Ca) was applied at a rate of 50 kg/ha for all row spacings. Seeds were treated with P-Pickle T® before sowing to control Ascochyta blight (360 g/L Thiram and 200 g/L Thiabenzazole active ingredients, 2 L mixed with 8 L of water applied at a rate of 1 L to 100 kg of seed). Seeds were treated with Group N Rhizobium inoculum at sowing using the peat slurry method.

The equipment used to place seed and fertiliser was a dual boot with a 50 mm wide combine point (Primary Sales Australia, Australia) which can place the fertiliser below the seed, on a spring release John Deere 700 series combine edge-on tine (John Deere, Queensland, Australia). The following press wheel was an adjustable pressure 80 mm wide chamfered “V” press wheel (set to 2 kg/cm width of press wheel) (Agmaster, Australia).

2.2.1 2007 Row spacing experiment

The experiment comprised four replicates and 18 treatments which were a complete factorial of two pre-season irrigation treatments (none or 80 mm of irrigation) and nine spacing and fertiliser combinations (four levels of row spacing by two levels of fertiliser placement plus an extra spacing/fertiliser combination with seed primed before sowing; Table 2.1).

Table 2.1. Spacing and fertiliser combinations.

<table>
<thead>
<tr>
<th>Row spacing</th>
<th>Fertiliser placement&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 cm (23RS)</td>
<td>X</td>
</tr>
<tr>
<td>50 cm (50RS)</td>
<td>With seed</td>
</tr>
<tr>
<td>75 cm (75RS)</td>
<td>5 cm below-seed</td>
</tr>
<tr>
<td>100 cm (100RS)</td>
<td></td>
</tr>
<tr>
<td>23 cm (23RS)</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>5 cm below primed seed</td>
</tr>
</tbody>
</table>

<sup>a</sup> 50 kg of double superphosphate/ha

The nine spacing and fertiliser treatments were randomly assigned within each of four replicates in a randomised complete block design. Half of the experiment was irrigated so that half of each spacing/fertiliser plot received irrigation and half did not (Figure 2.1). The irrigation treatment was not randomly assigned, due to operational requirements. Plots were 42 m long and 3.45, 4, 4.5 and 4 m wide respectively for the 23RS, 50RS, 75RS and 100RS. A
2 m wide buffer was located between the irrigated and non-irrigated halves of the plots. This experiment was reported in brief by French and Vance (2008).

Herbicide applications controlled the weeds that had germinated at that time which were a combination of ryegrass (*Lolium rigidum*), wild radish (*Raphanus raphanistrum*) and marshmallow (*Malva parviflora*). The area to be sown for the experiment was sprayed with 0.025 L/ha of Hammer® (240 g/L Carfentrazone-Ethyl) and 1 L/ha of Roundup CT® (Glyphosate 450 g/L) on 26 April. Before sowing, the herbicides, SpraySeed 250® at 2 L/ha (135 g/L Paraquat and 115 g/L Diquat), Simagranz® at 1.1 kg/ha (900 g/kg Simazine) and Treflan 1 L/ha (400 g/L Trifluralin and 500 g/L liquid hydrocarbons) were applied. Other applications of herbicide were SpraySeed 250® at 2 L/ha (135 g/L Paraquat and 115 g/L Diquat) and Select® at 0.25 L/ha (240 g/L Clethodim and 663 g/L liquid hydrocarbon) with the spray adjuvant Hasten® (704 g/L Ethyl and Methyl Esters of vegetable oil and 196 g/L non-ionic surfactants) on 26 July. To control native budworm (*Helicoverpa punctigera*), the insecticide Alpha Scud Elite® at 0.2 L/ha (100 g/L Alpha Cypermethrin and 760 g/l liquid hydrocarbons) was sprayed on 24 September and the insecticide 0.25 L/ha Sonic 200EC® was sprayed at 0.25 L/ha (668 g/L Liquid Hydrocarbons, 200 g/L Cypermethrin) on 11 October.

**Figure 2.1.** The plot design of the 2007 row spacing experiment completed at Merredin in Western Australia. Shading represents buffers. Row spacing 23 cm, 50 cm, 75 cm and 100 cm. Fertiliser placement W = with seed, B = below-seed, Seed priming NP = not primed, P = primed.
2.2.1.1 Soil water content

Soil water content was only recorded twice in the season. Gravimetric soil water content \((\theta_c)\) (Cresswell and Hamilton 2002) was measured before sowing (1 June) and close to the time of flowering (19 September) to 60 cm depth in selected plots.

2.2.1.2 Statistical analysis

The experimental design is similar to a strip-plot design except that the position of irrigation treatments is not randomised in each replicate. As such there are three components of residual variance to be considered when testing treatment effects: the variance between spacing/fertiliser main plots, the variance between irrigation main plots (within each replicate), and the variance between subplots (spacing/fertiliser/irrigation plots). A strip-plot analysis of variance (ANOVA) using data from irrigated and non-irrigated plots was used to estimate these variances and test the effects of spacing and fertiliser and their interaction with irrigation. Despite the non-randomisation of irrigation treatments these tests are valid. However, the main effect of irrigation was interpreted with caution as it could be expected that they would be biased due to the confounding effect of location. From ANOVA, the estimated means from the model and average least significant differences (l.s.d.) are reported. All analysis was completed using GenStat v11.1 (VSN International Ltd, United Kingdom).

2.2.2 2008 Row spacing experiment

The 2008 experiment comprised four replicates and six treatments which were a complete factorial of three levels of row spacing (23 cm, 50 cm, 75 cm) and two levels of soil water (with and without pre-season irrigation before sowing). In 2008 the widest row spacing treatment included in the 2007 trial (100RS treatment) was removed as this is the most likely to show yield decline in all conditions across chickpea, and is also the row spacing least likely to be implemented by local south-west WA farmers. In addition the 100RS treatment was removed from the 2008 experiment due to additional cost of fully implementing the soil water monitoring program. The fertiliser was placed 5 cm below the seed at sowing. The three row spacing treatments were randomly assigned within each replicate in a randomised complete block
design. As for the 2007 row spacing experiment, due to operational requirements, half of the experiment was irrigated so that half of each spacing plot received irrigation and half did not. Seventy five millimetres of water was applied to the irrigation treatments in ten irrigation events over 26 days (12 May to 6 June). Plots were 42 m long and 4, 3 and 2.75 m wide, respectively, for the 23RS, 50RS and 75RS treatments. A 2 m wide buffer was located between the irrigated and non-irrigated halves of each plot.

An error occurred at sowing of the 50RS plots. Three of the 50RS plots were discarded as plots (Plots 1, 5 and 9). To accommodate the error, three 50RS plots were sown at the end of the main plots, with extra 23RS and 75RS plots between; these are designated as plots 13 to 18 in Figure 2.2.

As in the 2007 trial, herbicide applications controlled the weeds that had germinated at that time which were a combination of ryegrass, wild radish and marshmallow. Insecticide applications controlled native budworm. The area to be sown for the experiment was sprayed with 0.025 L/ha of Hammer® (240 g/L Carfentrazone-Ethyl) and 2 L/ha of Roundup Powermax® (Glyphosate 540 g/L) on 24 April. Before sowing, the herbicides SpraySeed 250® at 2 L/ha (135 g/L Paraquat and 115 g/L Diquat) and Simagranz® at 1.1 kg/ha (900 g/kg Simazine) were applied. Other applications of herbicide were Status® at 0.25 L/ha (240 g/L Clethodim and 663 g/L liquid hydrocarbon) on 5 August, Broadstrike® at 25 g/ha (800 g/kg Flumetsulam) on 19 August and insecticide Fastac Duo® at 0.2 L/ha (741.9 g/L Liquid Hydrocarbons, 100 g/L Alpha-Cypermethrin) on 23 October.

**Figure 2.2.** Plot design of the chickpea row spacing experiment carried out in 2008 at Merredin, Western Australia. Row spacing at 23, 50 and 75 cm. Shading represents buffers.

<table>
<thead>
<tr>
<th>Non irrigated Plot Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non irrigated Row spacing</td>
<td>23</td>
<td>50</td>
<td>23</td>
<td>75</td>
<td>23</td>
<td>50</td>
<td>75</td>
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<td>50</td>
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<td>75</td>
<td>23</td>
<td>50</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Irrigated Plot Number</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
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<td>19</td>
<td></td>
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<tr>
<td>Irrigated Row spacing</td>
<td>23</td>
<td>50</td>
<td>23</td>
<td>75</td>
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<td>75</td>
<td>23</td>
<td>50</td>
<td>75</td>
<td>75</td>
</tr>
</tbody>
</table>

B = buffer
Plots 1, 5, and 9 were disregarded due to an error at sowing
2.2.2.1 Soil physical properties

Undisturbed soil aggregates and disturbed soil were sampled at 10 cm increments to 100 cm depth in a soil pit within the experimental plot after harvest. All samples were air dried and the disturbed samples were passed through a 2 mm sieve. Soil bulk density ($\rho_b$) was measured at each depth on three undisturbed soil aggregates by the intact clod method of Cresswell and Hamilton (2002). Particle size was measured at each depth on duplicate samples of the disturbed soil sample by the pipette method (Bowman and Hutka 2002) with the pre-treatment of 30 to 60 ml of hydrogen peroxide to ensure removal of organic matter. Samples were removed from the column by the pipette (25 ml) at two settling times to determine: (i) the mass of particles with equivalent spherical diameters <2 µm, and (ii) the mass of particles with equivalent spherical diameters <20 µm. Each of the samples were oven-dried at 105 °C for 24 hours. The final weights were then corrected to account for the mass of the dispersing agent, the conversion of the original samples from air-dry to oven-dry weights and the ratio of 25 ml sample volume from the 1000 ml total volume (Bowman and Hutka 2002). The percentage clay (clay %) was calculated from the mass of the <2 µm sample, the percentage silt (silt %) was calculated from the mass of the 2 to 20 µm sample and the percentage sand (sand %) was calculated from:

$$\text{sand} \% = 100 - \text{clay} \% - \text{silt} \%$$

2.2.2.2 Soil water content

Soil water content was measured by the gravimetric method before irrigation, at sowing and at installation of access tubes. Gravimetric soil water contents were converted to volumetric soil water contents ($\theta_v$) using the bulk density calculated for each horizon (Cresswell and Hamilton 2002). From 2 September onwards, soil water content was measured by the Sentek Diviner 2000 capacitance probe (Sentek sensor technologies, Stepney, South Australia) to 160 cm depth in four repetitions for each treatment and each distance from the seed row.

One access tube was placed in each plot at distances of: 12 cm from the plant row in the 23RS treatment, 12 and 25 cm from the plant row in the 50RS treatment, and 12, 25 and 37 cm from the plant row in the 75RS treatment. Volumetric soil water contents were recorded at
10 cm increments to 160 cm, eight times during crop growth. The Sentek Diviner readings of scaled frequency (SF) were calibrated to known measurements of $\theta_v$ for the 100 cm soil profile (Sentek 2001). Soil surrounding three access tubes was treated with different amounts of water with the aim of creating one saturated profile, one moist profile and one dry profile. After irrigation, the soil water content was read in each tube using the Sentek Diviner before the soil adjacent to each tube was sampled for soil water content. Three calibration equations were developed to cover the 0-10, 10-30 and 30-60 cm soil horizons (Figure 2.3). Calibration equations could not be developed for the 60-100 cm horizon. The calibration equation developed for the 30-60 cm horizon was used for the 60-160 cm depths. The regression equations for each horizon are:

1. 0-10 cm depth, $\theta_v = 45.54 \text{ SF}^{0.8201} r^2=0.96$;
2. 10-30 cm depth, $\theta_v = 38.05 \text{ SF}^{1.0013} r^2=0.83$; and
3. 30-60 cm depth, $\theta_v = 32.94 \text{ SF}^{0.8137} r^2=0.61$.

Figure 2.3. Relationship between volumetric water content ($\theta_v$) and scaled frequency counts (SF) from the Diviner 2000 for the 0-10 cm horizon (♦, —), 20-30 cm horizon (●, _ _ _), 30-60 cm horizon (▲, ........), and 60-100 cm (○). Symbols are data points and lines are fitted regression equations shown above in the text.
From the $\theta_v$ at each 10 cm depth increment down the soil profile, the profile soil water content (SWC) was calculated as the amount of water (mm) in the soil profile. The driest profile was recorded in March 2009, for the dry calibration hole. This was after a period of summer fallow following the harvest of the 2008 chickpea crop. An assumption was made that this was close to wilting point of the profile, as there had been no substantial rainfall in the previous period and no crop growth. This will be referred to as the $\theta_v$ at the estimated profile wilting point. The crop lower limit (CLL) was also estimated from measurements of soil water content during the cropping season. The CLL represents the soil water content below which a crop can no longer extract soil water, although water may still be available often below maximum root depth (Dalgliesh and Foale 2005). It is often determined at crop maturity or when the crop is under water stress. The CLL may differ from the profile soil water content at wilting point (-1500 kPa) and may differ between crops on the same soil type (Hochman et al. 2001; Dalgliesh and Foale 2005). In the 2008 experiment, the CLL was estimated from the profile soil water content at crop maturity and when plants were under water stress as indicated by leaf water potential (LWP) below -3 MPa (Siddique and Sedgley 1987; Leport et al. 1999; Leport et al. 2006).

2.2.2.3 Evapotranspiration

For each period of measurement, evapotranspiration (ET) was determined according to the equation:

$$ET = \Delta W + P - R - D$$

where $\Delta W$ was the change in water storage, $P$ was the rainfall during the period of measurement, $R$ was the soil surface runoff and $D$ the drainage below the measured soil profile. In this experiment runoff was assumed to be negligible as it was not observed and this is consistent with the lack of significant slope on the site. Drainage was also considered negligible as soil water measurements throughout the season showed very little change to soil water content at depths below 1 m, and is consistent with previous research which reported negligible drainage on similar soil types (Rickert et al. 1987; Siddique et al. 2001). Water use efficiency
of the chickpea for above-ground biomass (WUE) and grain (GWUE) at harvest were calculated from:

\[
\text{WUE} = \frac{\text{final above - ground biomass (kg/ha)}}{\text{ET}}
\]

\[
\text{GWUE} = \frac{\text{grain yield (kg/ha)}}{\text{ET}}
\]

2.2.2.4 Leaf water potential and relative water content

Leaf water potential (LWP) was measured on two uppermost fully expanded leaves from each plot using a pressure chamber (Model 1000 Pressure Chamber Instrument, PMS Instrument Company, USA). The petiole of the leaf was inserted into the pressure chamber directly after removal from the plant. After application of pressure in the chamber the end point (MPa) was recorded when the xylem sap was visible on the cut surface (Turner 1988; Leport et al. 1998). Measurements were taken at midday and pre-dawn on each of the two days (7 and 21 October) between flowering and crop senescence. Relative water content (RWC) of the leaves was measured on four days within the growing season (5 and 10 September, 8 and 22 October). In each plot, three uppermost fully expanded leaves were cut and placed into a sealed jar. The fresh weight (FW) of the leaf was recorded before 20 ml of water was placed in the jar with the leaf placed petiole down and the jar resealed. The samples were left overnight before the leaf was removed, dried with absorbent paper and the turgid leaf weight (TW) recorded. The leaf was oven-dried for 24 hours at 60 °C before the dry weight was recorded (DW). The RWC (%) was then calculated as:

\[
\text{RWC} = \left[ \frac{(FW - DW)}{(TW - DW)} \right] \times 100
\]

2.2.2.5 Statistical analysis

All extra 23RS and 75RS plots were included in all analyses except those that dealt with soil water analyses. A similar analysis of variance was carried as for the 2007 trial. However, because the additional plots meant the design was no longer balanced, a linear mixed model (fitted using the residual maximum likelihood (REML) procedure in GenStat v11.1) was used to
estimate the appropriate variance components and test the effects of row spacing and irrigation. There was some concern that the effect of the 50cm treatment might be biased as a result of adding the extra plots at one end of the trial. A contrast between the first four replicate blocks and the two additional blocks was included in the model to examine this effect. Across all variables tested this was not the case and the contrast term was removed from the model. The interpretation of the pre-season irrigation main effect was interpreted with caution as there was a confounding effect of location. The estimated means from the model and the average least l.s.d. were reported.

2.2.3 Plant measurements - 2007 and 2008

The crops were monitored for the date when 50% of plants had flowered, when 50% of plants had pods and for plant maturity. At various times during crop growth, quadrats of chickpea plants were sampled in each plot (Table 2.2). The quadrats were 50 cm long and comprised four rows in the 23RS treatment, two rows in the 50RS and 75RS treatments and one row in 100RS treatment. Plant growth parameters recorded for each quadrat where appropriate were: plant numbers, fresh and dry biomass (g), seed weight (g), pod numbers, pod fresh and dry weight (g), 100 seed weight (g), and weight (g) and number of seeds in 10 pods (Table 2.2).
Table 2.2. The chickpea plant parameters measured during crop growth and at harvest for the row spacing experiments established at Merredin in Western Australia during 2007 and 2008.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental year</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emergence</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadrat plant numbers</td>
<td>✓ (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Early growth</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadrat plant numbers</td>
<td>✓ (2)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Quadrat biomass weight</td>
<td>✓ (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flowering</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to 50 % flowering</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Quadrat plant numbers</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Quadrat biomass weight</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Quadrat pod weight</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Quadrat pod number</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Podding</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to 50 % podding</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Quadrat plant numbers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadrat pod weight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadrat pod number</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadrat biomass weight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Harvest</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to physiological maturity</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Quadrat plant numbers</td>
<td>✓ (2)</td>
<td>✓ (2)</td>
<td>✓ (2)</td>
</tr>
<tr>
<td>Quadrat seed weight</td>
<td>✓ (2)</td>
<td>✓ (2)</td>
<td>✓ (2)</td>
</tr>
<tr>
<td>Quadrat biomass weight</td>
<td>✓(2)</td>
<td>✓(2)</td>
<td>✓(2)</td>
</tr>
<tr>
<td>Weight and number of seeds in 10 pods</td>
<td>✓ (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 seed weight</td>
<td></td>
<td>✓ (2)</td>
<td></td>
</tr>
<tr>
<td>Quadrat pod number</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Quadrat pod weight</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Whole plot seed yield</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

*Indicates two quadrats were sampled from each plot
2.3 Results

2.3.1 Weather

The daily maximum, minimum temperatures and rainfall are shown for the 2007 and 2008 years in Figure 2.4. Weather data were collected daily from the Merredin Research Station, which was within 5 km of the experimental sites. The annual rainfall was greater in 2008 at 318 mm compared to 230 mm in 2007. The growing season rainfall (May to October) was 163 mm in 2007, and 232 mm in 2008.

![Figure 2.4. Weather parameters for the years a) 2007 and b) 2008. Daily minimum and maximum temperatures (°C) are shown as is daily rainfall (mm).](image)

**Figure 2.4.** Weather parameters for the years a) 2007 and b) 2008. Daily minimum and maximum temperatures (°C) are shown as is daily rainfall (mm).

2.3.2 Soil physical properties

Soil physical properties in the 2008 chickpea row spacing trial are presented in Table 2.3. The 2007 trial was 1.5 km from the 2008 trial on the same soil type. The soil surface was characterised as a clay (McDonald et al. 1998), with a bulk density of 1.62 g/cm³, over the
depth range 10 to 15 cm, clay percentage increased, thereafter soil texture remained uniform down the profile and the texture class remained as a clay.

Table 2.3.  The soil physical properties of the soil used in the 2008 chickpea row spacing trial in Merredin WA.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Bulk density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>51</td>
<td>11</td>
<td>38</td>
<td>1.62</td>
</tr>
<tr>
<td>10-20</td>
<td>39</td>
<td>12</td>
<td>49</td>
<td>1.62</td>
</tr>
<tr>
<td>20-30</td>
<td>38</td>
<td>13</td>
<td>49</td>
<td>1.75</td>
</tr>
<tr>
<td>30-40</td>
<td>33</td>
<td>17</td>
<td>50</td>
<td>1.63</td>
</tr>
<tr>
<td>40-50</td>
<td>35</td>
<td>14</td>
<td>51</td>
<td>1.67</td>
</tr>
<tr>
<td>50-60</td>
<td>34</td>
<td>14</td>
<td>52</td>
<td>1.68</td>
</tr>
<tr>
<td>60-70</td>
<td>39</td>
<td>12</td>
<td>48</td>
<td>1.64</td>
</tr>
<tr>
<td>70-80</td>
<td>39</td>
<td>12</td>
<td>49</td>
<td>1.64</td>
</tr>
<tr>
<td>80-90</td>
<td>41</td>
<td>11</td>
<td>47</td>
<td>1.71</td>
</tr>
<tr>
<td>90-100</td>
<td>41</td>
<td>11</td>
<td>48</td>
<td>1.81</td>
</tr>
<tr>
<td>100-110</td>
<td>39</td>
<td>12</td>
<td>49</td>
<td>1.85</td>
</tr>
</tbody>
</table>

2.3.3  2007 Row spacing

There were no apparent constraints due to disease (Ascochyta blight), insect (native budworm) or weeds in this trial, due to effective control measures as described in Section 2.2.1.

2.3.3.1 Chickpea crop growth and yield

The growth stages of the 2007 chickpea crop are presented in Table 2.4. The mean plant density did not alter considerably from emergence to harvest for any row spacing treatment (Figure 2.5). At emergence, the 50RS treatment had greater mean plant density than the other row spacing treatments ($P < 0.001$, l.s.d. 7.85). At emergence, the interaction between the three factors of irrigation, row spacing and fertiliser placement was significant ($P < 0.05$, l.s.d. 15.3). Within each irrigation treatment, the 100RS treatment had greater plant density when the fertiliser was placed below the seed, rather than with the seed. This was also the case within the 50RS, pre-season irrigated treatment.
Table 2.4. Phenology of crop development of the chickpea in the 2007 row spacing experiment.

<table>
<thead>
<tr>
<th>Plant phenology</th>
<th>Date</th>
<th>Days after sowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sowing date</td>
<td>26 June</td>
<td>87-94</td>
</tr>
<tr>
<td>50 % flowering</td>
<td>21 to 28 September</td>
<td>99-106</td>
</tr>
<tr>
<td>50 % podding</td>
<td>3 to 10 October</td>
<td>135</td>
</tr>
<tr>
<td>Crop physiological maturity</td>
<td>8 November</td>
<td></td>
</tr>
<tr>
<td>Crop harvest</td>
<td>26 November</td>
<td>153</td>
</tr>
</tbody>
</table>

Mean above-ground biomass was greater during the period flowering to harvest after pre-season irrigation than in the non-irrigated treatments ($P <0.001$) (Figure 2.6). The 75RS and 100RS treatments had the lowest early above-ground biomass (13 and 13.9 g/m², respectively) and were significantly less than all other irrigation by row spacing treatments ($P <0.05$, l.s.d. 3.6). At the time of 50 % flowering, the biomass of the 23RS and 50RS treatments was greater than the 75RS and 100RS treatments. By final harvest, row spacing and fertiliser treatments both had an effect on chickpea above-ground biomass. The 50RS treatment still had greater above-ground biomass than at wider row spacing of the 75RS and 100RS treatments. In treatments where the fertiliser was placed below the seed the mean above-ground biomass was 125 g/m² compared with 113 g/m² when the fertiliser was placed with the seed at sowing. The mean final above-ground biomass was 53 g/m² greater in the irrigated treatments compared to the non-irrigated treatments, with the lowest difference in the 100RS treatment at 45 g/m² and the greatest difference in the 50RS treatment at 59 g/m².
Figure 2.5. The mean chickpea plant density (plants/m²) in the quadrats sampled during the 2007 growing season at final emergence (1 August, 44 days after sowing (DAS)), early growth (15 August, 50 DAS), flowering (26 September, 92 DAS) and final harvest (26 November, 123 DAS) for a) 100 cm row spacing, b) 75 cm row spacing, c) 50 cm row spacing, and d) 23 cm row spacing. The error bars for each data point represents ± 1 standard error. The floating error bar on figure a) 100 cm row spacing represents the least significant difference (l.s.d.) at $P = 0.05$ for the interaction of irrigation x row spacing x fertiliser placement, averaged over all dates. Actual l.s.d. values were between 14.7 and 16.2.
Figure 2.6. The mean chickpea above-ground biomass (g/m²) in the quadrats sampled during the 2007 growing season at early growth (15 August, 50 days after sowing (DAS)), flowering (26 September, 92 DAS) and final harvest (26 November, 123 DAS) for a) 100 cm row spacing, b) 75 cm row spacing, c) 50 cm row spacing, and d) 23 cm row spacing. The error bars for each data point represents ± 1 standard error. The floating error bars on figure a) 100 cm row spacing, represent the least significant difference (l.s.d.) at \( P = 0.05 \) for the interaction of irrigation \( x \) row spacing \( x \) fertiliser placement, at each monitoring date.
At final harvest, all plant growth parameters sampled by quadrats showed significant differences within the individual treatments of irrigation, row spacing and fertiliser placement. The pre-season irrigated treatments had 33 g/m² (118 %) more grain yield than the non-irrigated treatments ($P < 0.001$) (Figure 2.7). Among the row spacing treatments, this difference was lowest at the 100RS treatment, with only 26 g more grain per square metre. As row spacing widened, the mean grain yield increased, however only the 75RS treatment was significantly greater than the 23RS treatment ($P < 0.05$, l.s.d. 5.48). When fertiliser was placed with the seed, the mean chickpea biomass and grain yield were both less than when fertiliser was placed below the seed ($P < 0.05$, l.s.d. 3.87).

When the whole plots were machine harvested, grain yield of the 50RS treatment was significantly greater than the other row spacing treatments ($P < 0.001$, l.s.d. 83) (Figure 2.7). Pre-season irrigation increased the grain yield by only 191 kg/ha in the 100RS treatment but the difference in the 50RS treatment was 347 kg/ha, a 107 and 104 % increase in grain yield respectively.

Harvest index (HI) was greater after pre-season irrigation than in the non-irrigated treatment ($P < 0.01$) at 0.4 and 0.28, respectively (Figure 2.8). With increased row spacing, there was a positive linear increase in HI from 0.29 at the 23RS treatment to 0.39 at the 100RS treatment ($P < 0.001$, l.s.d. 0.038).
Figure 2.7. The mean chickpea grain yield determined by a) quadrat sampling (g/m²) and b) whole plot machine harvest (kg/ha). The floating error bar on each figure represents the least significant difference (l.s.d.) at $P = 0.05$ for the interaction of irrigation x row spacing x fertiliser placement, either within the irrigation treatments (left) or between the irrigation treatments (right).

Figure 2.8. The mean harvest index of chickpea from the quadrat samples. Black bars indicate pre-season irrigation, open bars indicate non-irrigated treatments. The floating error bar on each figure represents the least significant difference (l.s.d.) at $P = 0.05$ for the interaction of irrigation x row spacing either within the irrigation treatments (left) or between the irrigation treatments (right).
2.3.3.2 Soil water content

Soil water content was measured before sowing on 1 June to a depth of 60 cm (Figure 2.9). At this time, the pre-season irrigated profile held approximately 22 mm more water in the top 50 cm of the soil profile. Soil water content was again measured on 19 September, in one plot each of the pre-season irrigated and non-irrigated 23RS and 100RS treatment plots (Figure 2.10). Indications from this data are that the wider row spacing had greater soil water remaining in the soil profile, mainly due to a greater proportion of water at the 50 cm distance from the seed row at 20-30 cm depth.

Figure 2.9. The mean gravimetric soil water content (%) of the soil profiles of the pre-season irrigated (filled circles) and non-irrigated (open circles) plots on 1 June 2007. Error bars represents ± 1 standard error (n = 6 to 8 from 0-40 cm, n = 2 for 50-60 cm).
2.3.4 2008 Row spacing

There were no apparent constraints due to disease (Ascochyta blight), insect (native budworm) or weeds in this trial, due to effective control measures as described in Section 2.2.2.

2.3.4.1 Chickpea crop growth and yield

The growth stages of the crop are presented in Table 2.5. Field visits did not occur to coincide with time of 50 % podding or plant maturity, so the characteristics of the crop on the closest date of a field visit are reported. The first biomass sampling was before flowering on 10 September (83 DAS), the next two samplings covered the period from the beginning of podding, 8 October (111 DAS) to after final podding, 22 October (125 DAS).
Table 2.5. Phenology of crop development of the chickpea in the 2008 row spacing experiment.

<table>
<thead>
<tr>
<th>Plant phenology</th>
<th>Date</th>
<th>Days after sowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sowing date</td>
<td>19 June</td>
<td></td>
</tr>
<tr>
<td>50 % flowering</td>
<td>24 September to 1 October</td>
<td>97-104</td>
</tr>
<tr>
<td>10 % podding</td>
<td>8 October</td>
<td>111</td>
</tr>
<tr>
<td>Crop physiological maturity</td>
<td>45 to 70 % senesced, 7 November</td>
<td>141</td>
</tr>
<tr>
<td>Crop harvest</td>
<td>10 December</td>
<td>174</td>
</tr>
</tbody>
</table>

The 75RS treatment had significantly lower plant density (plants/m²) than the 23RS and 50RS treatments throughout the season ($P < 0.01$) (Figure 2.11). However, the within-row plant population was greater in the 75RS treatment, compared to the 23RS and 50RS treatments at 24, 17 and 9 plant/m, respectively.

![Figure 2.11](image)

From 83 to 125 DAS, the mean above-ground biomass of the chickpea crop in the pre-season irrigated treatments was greater than the non-irrigated treatment ($P < 0.05$) (Figure 2.12). Across all sampling dates, above-ground biomass decreased with increasing row spacing. Up until 125 DAS, the 23RS and 50RS treatments had significantly higher above-ground biomass...
than the 75RS treatment ($P<0.005$). By harvest, the 23RS treatment had mean above-ground biomass greater than both the 50RS and 75RS treatments ($P<0.001$).

Figure 2.12. The mean above-ground biomass (g/m$^2$) from the quadrats collected during the growing season for 23 cm (●), 50 cm (▲) and 75 cm (■) row spacing treatments with (closed symbol) and without (open symbol) pre-season irrigation. Error bars indicate the average least significant difference (l.s.d.) at $P=0.05$ for the irrigation treatment (IRR) and the row spacing treatment (RS) where they were significantly different at each date of sampling.

The mean number of pods per unit area (quadrat samples) was negatively related to row spacing on 8 October (111 DAS) after sowing ($P<0.01$). With each increase in row spacing there was a significant decline in pod numbers (Figure 2.13). On 22 October (125 DAS) and at final harvest, the pre-season irrigated treatments had higher mean pod numbers and pod weights than the non-irrigated treatments ($P<0.05$). The 23RS and 50RS treatments had greater pod numbers and pod weights than the 75RS treatment on the 22 October (125 DAS) ($P<0.001$). However, at final harvest the 23RS treatment had higher mean pod weights and numbers than both 50RS and 75RS treatments ($P<0.05$) (Figure 2.13).

The 23RS and 50RS treatments had greater crop growth (in terms of above-ground biomass, pod weight and pod number) during the season than the 75RS treatment. At final harvest, 50RS treatment was no longer greater than the 75RS treatment with the 23RS treatment clearly having greater final crop growth.
Figure 2.13. The mean a) pod number (pods/m\(^2\)) and b) pod weight (g/m\(^2\)) from the quadrats collected during the growing season from the 23 cm (●), 50 cm (▲) and 75 cm (■) row spacing treatments with (closed symbol) and without (open symbol) pre-season irrigation. Error bars indicate the average least significant difference (l.s.d.) at \(P = 0.05\) for the irrigation treatment (IRR) and the row spacing treatment (RS) where they were significantly different at each date of sampling.
The machine harvested grain yields were between 632 and 1150 kg/ha (Figure 2.14). There were no interactions between the irrigation and row spacing treatments for the machine harvested grain yield. The 23RS treatment had a higher mean grain yield than the 50RS and 75RS treatments \( (P < 0.001) \) and the pre-season irrigated treatments had higher mean grain yields than the non-irrigated \( (P < 0.01) \).

![Figure 2.14. Final chickpea grain yields (kg/ha) collected by machine harvest. The error bars indicate the average least significant difference (l.s.d.) at \( P = 0.05 \) either within irrigation treatment (IRR) or between the irrigation treatments. Closed symbols represent with and open symbols without pre-season irrigation.](image)

There was a linear interaction between irrigation and row spacing treatment in the quadrat measurements of final grain yield. With pre-season irrigation for every centimetre increase in row spacing, grain yield decreased by -1.14 ± 0.33 g/m² \( (P = 0.054) \). The 23RS, pre-season irrigated treatment had higher yields than all other treatments at 144 g/m² compared to yields of 90 to 113 g/m² \( (P < 0.054) \) (Figure 2.15). Harvest index was between 0.47 and 0.51 for all treatments. There was no interaction or irrigation effect on HI but the 75RS treatment had a higher mean HI than all other row spacing treatments \( (P = 0.01) \) (Figure 2.15).
Figure 2.15. Crop growth parameters measured from the quadrats sampled at final harvest of the chickpea plots on the 10 December 2008. Means are presented for grain yield (g/m²) and harvest index. Closed symbols represent pre-season irrigation and open symbols without irrigation. The error bars indicate the average least significant difference (l.s.d.) at $P=0.05$ either within irrigation treatment (IRR) or between the irrigation treatments.
2.3.4.2 Crop water stress

There was no row spacing or irrigation effect on LWP. Leaf water potential was higher earlier in the season (7 October, 110 DAS) than later (21 October, 124 DAS) (Figure 2.16). On both occasions, the midday readings were lower than the pre-dawn readings measured on the following morning, indicating that the crop was able to recover overnight. The mean LWP on 21 October were below -3 MPa for all treatments, indicating the crop was under greater water stress at this time in comparison to the previous measurement.

Relative water content was lower in the non-irrigated treatments compared to the pre-season irrigated treatments on 5 September (78 DAS) and 22 October (125 DAS) ($P < 0.05$) (Figure 2.16). Across all dates of sampling, the RWC in the non-irrigated plots was between 71.5 and 83.0%, whilst in the pre-season irrigated plots it ranged between 78.4 and 85.2%.

Overnight on 21 October there was 5.6 mm of rainfall, which would have contributed to the recovery of the crop and account for an overall increase in mean LWP across all plots from -3.5 to -1.4 MPa the following morning. In addition, the pre-dawn measurement of RWC (125 DAS) was similar to the RWC of the previous measurement on the 8 October (111 DAS), indicating that the crop was still able to recover from the stress it had been under on the previous day.
Figure 2.16. The mean of a) leaf water potential (LWP) (MPa) and b) relative water content (RWC) (%) of the chickpea crop under row spacing treatments of 23 cm (filled bar), 50 cm (hatched bar) and 75 cm (checked bar) with (black) or without (green) pre-season irrigation during the 2008 growing season. In figure a) the error bars for each data point represent 1 standard error. In figure b) where significant differences occur between RWC of the irrigation treatment the l.s.d. at $P = 0.05$ was presented as a floating error bar above the appropriate sampling date, n.s. indicates not significant.
Soil water profiles

Soil water content was measured before sowing of the chickpea and during crop growth. The profile SWC (0-60 cm depth) before irrigation of the trial began was 122 mm, and the distribution of this water with depth is shown in Figure 2.17. Between this time and sowing of the chickpea crop on the 19 June 2008, there was 24.6 mm of rainfall and an additional 75 mm of water was applied to the pre-season irrigation treatments. At sowing, the mean profile SWC to 60 cm in the pre-season irrigated plots was 141 mm, whilst in the non-irrigated plots it was 127 mm. Twenty one days later, after 18.8 mm of rainfall, the mean profile SWC in the non-irrigated plots was 120 mm and in the pre-season irrigated plots 174 mm (Figure 2.17). At sowing and on 10 July (21 DAS), the soil water content was greater in the pre-season irrigated plots than the non-irrigated plots in the surface 10 cm of soil ($P < 0.05$).

![Figure 2.17. Volumetric water content (%) of the soil profile before irrigation began (1 May, $n=2$) (triangle), at sowing (19 June, $n=3$) (squares), and 21 days after sowing (DAS) (10 July, $n=3$) (circles). Open symbols indicate the non-irrigated treatment, closed symbols the pre-season irrigated treatment. The error bars represent ± 1 standard error of the mean.](image)

The starting profile SWC (0-60 cm) at 1 May and the inputs of water in the form of irrigation and rainfall from 1 May until 2 September are summarized in Table 2.6. This period includes sowing on 19 June and uses measured values of soil water content (0-60 cm) and
estimates of soil water content (60-100 cm) to determine the profile SWC at sowing to 100 cm depth for the pre-season irrigated and non-irrigated profiles. The soil water content measured at sowing on the 19 June at 60 cm depth (22 %) was used as an estimate of the soil water content of the deeper depth from 60-100 cm. This assumption was made as up until the 19 June at 60 cm depth there was little difference in soil water content between dates of measurement or treatments and often soil water content remains constant deeper in the profile (Figure 2.17). These calculations have then been extended to approximate the profile SWC on 2 September (75 DAS) when the first measurement with the Sentek Diviner probe was taken. A comparison of the values measured with the Sentek Diviner probe versus those calculated can determine the accuracy of the calibrated Sentek Diviner values of $\theta_v$ for assessing changes in profile and horizon soil water content. The calculated values were higher than the measured values of profile SWC by 28 and 32 mm, respectively, for the pre-season irrigated and non-irrigated profiles. The calculated values do not take into consideration crop water use between sowing and time of measurement, and this difference may even be used as an indicator of crop water use in the period from sowing until 2 September.
Table 2.6. The measured profile soil water content (SWC) (mm) to 60 cm depth and approximations of profile SWC to 100 cm depth between 1 May and 2 September 2008 (75 days after sowing, DAS) during the chickpea growing season. The inputs of water to the experiment via irrigation and rainfall are also shown along with the mean profile SWC of the pre-season irrigated and non-irrigated plots as measured by the Sentek Diviner soil water capacitance probe on 2 September.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event (rainfall / irrigation / soil water monitored)</th>
<th>Water (mm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 May</td>
<td>Soil water content 0-60 cm depth</td>
<td>122</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 May to 19 June</td>
<td>Rainfall</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Irrigation</td>
<td>75</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>19 June (sowing)</td>
<td>Soil water content 0-60 cm</td>
<td>141</td>
<td>127</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil water content 60-100 cm¹</td>
<td>88</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total water 0-100 cm</td>
<td>229</td>
<td>215</td>
<td></td>
</tr>
<tr>
<td>19 June to 2 September (75 DAS)</td>
<td>Rainfall</td>
<td>108</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>2 September</td>
<td>Approximate water in 100 cm profile</td>
<td>337</td>
<td>323</td>
<td></td>
</tr>
<tr>
<td>2 September</td>
<td>Sentek Diviner reading of mean water in 100 cm profile (± 1 standard error)</td>
<td>309 ± 3.6</td>
<td>291 ± 3.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(n =24)</td>
<td>(n =22)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ assume 22 % water by volume in 60-100 cm layer based on the 60 cm soil water content reading on the 19 June 2008 (Figure 2.17).

The profile SWC at wilting point was estimated to be 267 mm/m and at the CLL 283 mm/m.

In the 23RS and 50RS treatments, the pre-season irrigated profiles had more SWC than the non-irrigated profiles at both 12 and 25 cm from the seed row at 2 to 23 September (75 to 96 DAS) (Figures 2.18 and 2.19). Whilst the differences were all greater than 20 mm of water, significant differences were only found on 10 and 23 September (83 and 96 DAS), at the 12 cm distance from the seed row, and all DAS at the 25 cm distance from the seed row (P <0.05). Soil water content continued to decline until 7 October (110 DAS) when the profile soil water content increased due to 48 mm of rainfall in the preceding 13 days.

The 75RS treatment also had an overall decline of SWC from 2 to 23 September (75 to 96 DAS) followed by an increase in SWC on the 7 October (110 DAS) (Figure 2.20). However, during this period, at 12 and 25 cm from the seed row the non-irrigated plots had a profile SWC similar to the pre-season irrigated plots. Only at 37 cm from the seed row was the profile SWC in the pre-season irrigated plots greater than the non-irrigated plots. The difference in profile SWC was >10 mm of water but not significant (P <0.05).
From 7 October (110 DAS) to maturity in the 75RS treatment at 12 and 25 cm from the row, the SWC of the non-irrigated profiles was greater than the pre-season irrigated profiles. Whilst the pre-season irrigated profiles showed a decreasing trend in SWC to crop maturity, the non-irrigated profiles showed an increasing trend (Figure 2.20). In the 23RS and 50RS treatments, the profile SWC converged for the non-irrigated and pre-season irrigated treatments on 22 October (125 DAS), after which the irrigated profile SWC were less than the non-irrigated.

Rainfall totalled 37.5 mm over the period from 7 October to 7 November (110 to 141 DAS). Twenty nine millimetres of rain fell in the nine days before 7 November (141 DAS), 16 mm of which fell one day before this reading was taken, but seemed to have little effect on the SWC of the 23RS treatment. The treatments which showed the greatest rise in SWC after this rainfall event were at 12 cm from the seed row in the non-irrigated treatments.
Figure 2.18. The mean profile soil water content (SWC) (mm) in a 100 cm profile measured during the chickpea crop growing season in the 23 cm row spacing treatments, with (full line) and without (dashed line) pre-season irrigation. Clear squares represent the cumulative rainfall between measurements of SWC. Floating error bars for each measurement indicate the least significant difference (l.s.d.) at $P=0.05$ for the irrigation x probe spacing interaction.

Figure 2.19. The mean profile soil water content (SWC) (mm) in a 100 cm profile measured during the chickpea crop growing season in the 50 cm row spacing treatments, with (full line) and without (dashed line) pre-season irrigation, at 12 cm (♦) and 25 cm (♦) from the seed row. Clear squares represent the cumulative rainfall between measurements of SWC. Floating error bars for each measurement indicate the least significant difference (l.s.d.) at $P=0.05$ of the irrigation x probe spacing interaction.
Figure 2.20. The mean profile soil water content (SWC) (mm) in a 100 cm profile measured during the chickpea crop growing season in the 75 cm row spacing treatments at 12 cm (♦), 25 cm (■) and 37 cm (▲) from the seed row, with (full line) and without (dashed line) pre-season irrigation. Clear squares represent the cumulative rainfall between measurements of SWC. Floating error bars for each measurement indicate the least significant difference (l.s.d.) at $P = 0.05$ of the irrigation x probe spacing interaction.

Figures 2.21 to 2.23 show the mean changes in soil water content (mm) of each 10 cm soil layer from the 10 September (83 DAS) to harvest (174 DAS). Each line on the graph represents a single 10 cm increment of soil profile depth, starting at 10 cm on the top of each graph to 100 cm depth at the base of the graph. Examination of each 10 cm layer in the soil profile (Figures 2.21 to 2.23) indicates pattern of water use with depth in the profile (Siddique and Sedgley 1987). An increase or decrease of the line for each day the soil water content was measured indicates additions or losses of water from that soil depth. Each graph represents the soil profile in the 23RS, 50RS or 75RS treatments, with or without pre-season irrigation and at one of three distances from the seed row (12, 25 or 37 cm). In the 23RS treatment and 12 cm from the seed row, changes to the soil water content occur to 50 cm depth in the pre-season irrigated treatment and 70 cm depth in the non-irrigated treatment (Figure 2.21). This change in soil water content at depth becomes most visible at 110 DAS, after significant rainfall events.
In the 50RS treatment the change in soil water content also occurs deeper in the non-irrigated (70 cm depth) compared to the pre-season irrigated treatment (40 cm depth) regardless of the distance from the seed row (Figure 2.22). In the 75RS treatment that was not irrigated, the depth to which changes in the soil water content occurred across all distances (12 to 37 cm) from the seed row was 90 to 70 cm depth. By contrast, in the pre-season irrigated treatment there were changes to 50 cm depth at all distances from the seed row (Figure 2.23).
Figure 2.22. The mean change in water storage (mm) of each 10 cm soil layer under a) the 50 cm row spacing with irrigation measured 12 cm from the seed row, b) the 50 cm row spacing with irrigation measured 25 cm from the seed row, c) the 50 cm row spacing with no irrigation measured 12 cm from the seed row, and d) the 50 cm row spacing with no irrigation measured 25 cm from the seed row (n = 4).
Figure 2.23. The mean change in water storage (mm) of each 10 cm soil layer under a) the 75 cm row spacing with irrigation measured 12 cm from the seed row, b) the 75 cm row spacing with irrigation measured 25 cm from the seed row, c) the 75 cm row spacing with irrigation measured 37 cm from the seed row, d) the 75 cm row spacing with no irrigation measured 12 cm from the seed row, e) the 75 cm row spacing with no irrigation measured 25 cm from the seed row, and f) the 75 cm row spacing with no irrigation measured 37 cm from the seed row (n = 4).
The total and cumulative evapotranspiration taking into account rainfall additions during the season, provide an estimation of crop water use (Figures 2.24 to 2.27). The total ET of the chickpea crop varied across treatments of row spacing and irrigation (Figure 2.24). Within the same row spacing treatment and distance from the seed row all pre-season irrigated treatments were significantly greater in the total ET than the non-irrigated treatments except for the 23RS treatment and the 50RS treatment at 25 cm from the row. Within the irrigation treatments, there were no significant differences with row spacing or probe spacing. At 12 cm from the seed row in the 23RS treatment, there was greater total ET than from the same distance from the row in the 75RS treatment in the non-irrigated plots. With greater distance from the seed row (that is 12, 25 or 37 cm) to the ET measurement in the 75RS treatment, the total ET increased. These differences may be attributed to the pattern of growth of the chickpea plants under the different treatments.

![Figure 2.24](image)

**Figure 2.24.** The mean of total evapotranspiration (mm) (sowing to harvest) for each row spacing treatment with (filled bars) and without (unfilled bars) pre-season irrigation. Probe spacing indicates the distance from the seed row where measurement was taken. Floating error bars for each measurement indicate the average least significant difference (l.s.d.) at $P = 0.05$ between the irrigation treatments and within the separate pre-season irrigation (PRE-IRR) and non-irrigated (NON-IRR) treatments ($n = 4$). See Section 2.2.2.3 in text for the calculation of evapotranspiration.
Figures 2.25 to 2.27 show the cumulative evapotranspiration (ET\textsubscript{cum}) during the growing season at each irrigation and row spacing treatment and at each distance measured from the seed row. These show the pattern of water use through the season, the differences between the pre-season irrigated and non-irrigated treatments and how the crop may be accessing water through the season at distances from the seed row. In the 23RS and 50RS treatments, it seems that the non-irrigated treatments had greater ET up to 7 October (110 DAS), whereas in the 75RS treatment the pre-season irrigated treatments had greater ET through the season at 12 and 25 cm from the seed row, but similar water use occurred regardless of irrigation early in the season at 37 cm from the seed row. The similar values of ET\textsubscript{cum} for the 75RS treatment at 37 cm from the seed row could be an indication of the lack of plant water use up to this time suggesting that soil evaporation was the dominant water loss process here. There was no significant interaction between irrigation, row spacing and probe spacing using REML. From 7 October until 7 November (110 to 141 DAS) the non-irrigated treatment always had a mean ET\textsubscript{cum} less than the pre-season irrigated treatment ($P <0.05$).

Figure 2.25. The mean cumulative evapotranspiration (mm) in a 100 cm profile measured during the chickpea crop growing season in the 23 cm row spacing treatments at 12 cm from the seed row, with (closed symbol) and without (open symbol) pre-season irrigation. Floating error bars indicate the least significant difference (l.s.d.) at $P =0.05$ for the interaction of irrigation x probe spacing for each date of measurement.
Figure 2.26. The mean cumulative evapotranspiration (mm) in a 100 cm profile measured during the chickpea crop growing season in the 50 cm row spacing treatments at  a) 12 cm from the seed row, and b) 25 cm from the seed, with (closed symbol) and without (open symbol) pre-season irrigation. Floating error bars indicate the least significant difference (l.s.d.) at $P = 0.05$, for the interaction of irrigation x probe spacing for each date of measurement.
Figure 2.27. The mean cumulative evapotranspiration (mm) in a 100 cm profile measured during the chickpea crop growing season in the 75 cm row spacing treatments at a) 12 cm from the seed row, b) 25 cm from the seed row, and c) 37 cm from the seed row, with (closed symbol) and without (open symbol) pre-season irrigation. Floating error bars indicate the least significant difference (l.s.d.) at $P=0.05$, for the interaction of irrigation x probe spacing for each date of measurement.
Water use efficiency (WUE) and grain water use efficiency (GWUE) were calculated from the ET and biomass or grain yields, respectively, using the soil water data 12 cm from the seed row only (Table 2.7). The mean GWUE was significantly greater in the pre-season irrigated treatment at 6.28 kg/ha/mm, compared with the non-irrigated treatment at 5.21 kg/ha/mm ($P < 0.01$). However, in the pre-season irrigated treatments, the 23RS treatment was higher in WUE than the 75RS treatment ($P < 0.05$).

Table 2.7. The biomass water use efficiency (WUE) and grain water use efficiency (GWUE) for the 2008 Merredin row spacing trial.

<table>
<thead>
<tr>
<th>Row space (cm)</th>
<th>WUE (kg/ha/mm)</th>
<th>GWUE (kg/ha/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-season irrigated</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>17.7 $^a$</td>
<td>6.74</td>
</tr>
<tr>
<td>50</td>
<td>15.1 $^{ab}$</td>
<td>6.27</td>
</tr>
<tr>
<td>75</td>
<td>12.8 $^b$</td>
<td>5.82</td>
</tr>
</tbody>
</table>

$P$-value

| Irrigation | n.s. | $< 0.01$ |
| Row spacing | n.s. | n.s. |
| Irrigation x Row spacing | $< 0.05$ | n.s. |

I.s.d.

| Irrigation | 0.614 |
| Irrigation x Row spacing | |
| Within irrigation treatment | 3.58 |
| Between irrigation treatment | 4.41 |

Values within a column with the same superscript are not significantly different.
n.s. indicates not significant
I.s.d. indicates the least significant difference at $P = 0.05$
2.4 Discussion

2.4.1 Chickpea grain yield and biomass

Water limited yield potential is determined by the growing season rainfall, soil water storage and plant available water (Whish et al. 2005). Based on May to October rainfall (referred to as growing season rainfall; Thompson et al. 1997) there were differences in yield potential between 2007 and 2008. May to October rainfall was 163 mm in 2007, and 232 mm in 2008, values that were below and above, respectively, the long term average (1911 to 2008) for growing season rainfall at Merredin, WA which is 212 mm.

The 2008 season could be considered to have high yield potential (232 mm growing season rainfall), and yield response was consistent with earlier reports that wide rows decreased grain yield when there was high yield potential (Figure 2.14) (Riethmuller and MacLeod 2002; Whish et al. 2002). In the 2007 trial, a season with lower yield potential (163 mm growing season rainfall), the 50RS and 75RS treatment had increased yield compared to the narrow row spacing as has been reported previously at other locations (Figure 2.7) (Beech and Leach 1989b; Felton et al. 1996; Riethmuller and MacLeod 2001). In 2007, the 23RS and 50RS treatments had the greatest biomass at flowering which indicates potential yields were greater than at the wider row spacing. Previous authors suggested that plants in narrow rows use more of the available stored water early in the season than plants in wide rows (Riethmuller and MacLeod 2002; French and Harries 2006). This would lead to lower final yields in the 23RS treatment because soil water became more limiting than in the 50RS treatment due to low growing season rainfall. However, the previous studies lacked direct evidence of altered water use patterns with different row spacing.

In both years, pre-season irrigation provided 14 to 20 mm more stored water in the soil profile at sowing. Whilst the overall yields were consistently greater with pre-season irrigation within each year, the difference in yield with pre-season irrigation did not vary with row spacing. In 2008, pre-season irrigation increased yield by 54 % whilst in 2007 yields were increased by 133 % compared with the non-irrigated plots (fertiliser placed below the seed only). The soil water profile storage measurements from the 2008 trial indicate that any
advantage of higher initial soil water content has been lost by 110 DAS, which was before reproductive growth had begun (Figures 2.18 to 2.20). Therefore the primary effect of the pre-season irrigation was on increased plant biomass (Figure 2.12) which in turn resulted in uniformly higher grain yields across treatments of row spacing. Although yields were considerably improved across all row spacings in the low rainfall year (2007) the additional water made available with pre-season irrigation has not caused the narrower row spacing to have greater yields than the wider row spacing. Whilst the addition of pre-season irrigation increased profile SWC, this has not led to seasonal conditions improving in 2007 to that of a high yield potential season. For example, chickpea yields did not change from chickpea at wide row spacing having higher yields to chickpea at narrow row spacing having higher yields. When soil water content was measured in 2008 this showed that the advantage of increased soil water at sowing was lost by the start of reproductive growth; in 2007 a similar scenario may also have occurred. This means that in 2007 the chickpea plants in both pre-season irrigated and non-irrigated treatments relied on growing season rainfall for pod set and seed filling.

From previous research, the links between yield potential and row spacing are contradictory. For example, in south-west WA in non-limiting water conditions chickpea yields were not affected by row spacing, and in northern NSW and southeast Queensland wide row spacings had no effect on yield in low yield potential conditions (Beech and Leach 1989b; Felton et al. 1996; Riethmuller and MacLeod 2001). In summer-dominant rainfall environments of India and Pakistan, chickpea grain yields have been reported to both increase and decrease with increased row spacing regardless of growing season rainfall (Saxena and Sheldrake 1974; Khan et al. 2001; Khan et al. 2010). Riethmuller and MacLeod (2001) suggested the response of grain yields to row spacing depended on whether soil water became limiting at grain filling.

As discussed above (see Chapter 1.4.2.2), the relationship between plant population and grain yield is inconsistent. Jettner et al. (1999) suggested that the relationship between plant population and grain yields depends on yield potential. In the 2007 and 2008 experiments, the treatment with the highest plant population did not consistently achieve the highest yield. Notably in the high yield potential year (2008), PPD was lower overall but crops achieved higher grain yields than in 2007 with higher PPD. Nevertheless in 2008, with higher PPD in the
23RS treatment, yield was also higher. By contrast under low yield potential in 2007 the wider row spacing, with the lowest PPD, achieved the higher yield. Hence the present results support the proposal that the relationship of PPD to yield in chickpea depends on growing season rainfall which in turn is closely related to yield potential (Jettner et al. 1999; Turner 2004). A possible explanation of these results is that where growing season rainfall is limiting, high PPD and associated growth of biomass uses available soil water leaving little available for seed development (Jettner et al. 1999). However, there has been little direct evidence of soil profile water storage or crop water use patterns to support this deduction.

The effect of sowing rate and row spacing configurations on chickpea grain yield has also been found to be inconsistent. In experiments in south-west WA at sowing rates of 120 to 150 kg/ha, Riethmuller and MacLeod (2000, 2001) reported that final plant establishment was unaffected by row spacings (within each sowing rate) and grain yield did not vary in either a high yield potential season (1999, 318 mm, Merredin) or a low yield potential season (2000, 142 mm, Mullewa). By contrast, at constant plant-to-plant spacing within the row, in the dry year, there was a slight yield decline with wide rows, reflecting the lower overall plant population per unit area.

Plant density in the 2007 and 2008 years varies across row spacing, with the wider row spacing having a lower plant density (Figures 2.5 and 2.11). The row spacing configuration has affected the final PPD in both years and in the following sections the effects this has on crop water uptake and ET in the 2008 experiment will be further elaborated. Other researchers have stated that increasing seeding rate in chickpea has resulted in lower seedling emergence (Beech and Leach 1989b; Jettner et al. 1999; Yau 2005). To achieve wider row spacing without decreasing PPD across treatments, seeding rate must be increased at wider row spacing. In both 2007 and 2008, PPD decreased with increasing row spacing, even though at wider row spacing there were more plants per metre within-rows. Poor germination and emergence can be a result of unfavourable seed-bed water and temperature conditions regardless of plant density. In addition, with wider row spacing the greater within-row seed density can result in greater plant-to-plant competition for water and nutrients which may decrease germination and emergence (Jettner et al. 1999; Riethmuller and MacLeod 2001). The soil water content within the seed-
bed was not measured in the 2007 or 2008 experiments however, competition for resources may account for the lower PPD at the wider row spacings in both years. The mechanical processes at sowing can also affect the success of germination and emergence of seed with greater physical damage to the seed and seed coat lowering establishment rates at wide row spacing (Jettner et al. 1999). Large chickpea seeds are more prone to damage at seeding than smaller seeded species and hence this species may be more sensitive to reduced final plant density at the wide row spacing (Jettner et al. 1999). The practice of sowing into wider rows has also been found to be confounded with decreased sowing depth (Riemuller and MacLeod 2000). In the 2007 and 2008 trials at Merredin there was a greater mass of chickpea seeds moving through the seeder to create the seed density required for the >75RS treatments compared with the narrower row spacing treatments. Whilst seed damage and shallow sowing may have affected plant establishment at wider row spacing there were no measurements taken to verify this.

2.4.2 Crop water use as affected by row spacing

The difference in yields across the row spacing treatments can be attributed to in-season rainfall, profile SWC, and as discussed above, to plant population and arrangement. Crop water use of the chickpea plants across the row spacing treatments was examined through the profile SWC and ET in the 2008 experiment. Before sowing, 100 mm of water was applied as irrigation or rainfall, but this contributed only 14 mm of additional water in the 100 cm soil profile of the pre-season irrigated treatments (Table 2.6). This indicates that the pre-season irrigation was comparatively ineffective and a large proportion of the applied water was removed as evaporation before sowing, since runoff and drainage would be negligible in this soil type (Rickert et al. 1987; Siddique et al. 2001). The similar soil water content of the pre-season irrigated and non-irrigated at 40 and 60 cm in the soil profiles at two months after irrigation in 2007 and 2008 (Figures 2.9 and 2.17) is evidence for the lack of profile drainage from pre-season irrigation.

Across all treatments, crop water use and soil evaporation are indicated by a decrease in profile SWC, while significant contributions of rainfall were indicated by increases in profile SWC. Seventy five days after sowing there was, on average, an 18 mm increase in profile SWC
in the pre-season irrigated over non-irrigated treatments (Table 2.6). This difference in profile SWC was dependent on the row spacing treatment and varied with the distance from the seed row. The 23RS and 50RS treatments (monitored at 12 and 25 cm from the seed row) had 24 to 38 mm more soil water in the pre-season irrigated than the non-irrigated profile. These differences in profile SWC between the pre-season irrigated and non-irrigated plots remained until 110 DAS (Figures 2.18 and 2.19). Across both the 12 and 25 cm distance from the seed row there were similar trends in declining profile SWC due to crop water use, which seemed to be proportional between the pre-season irrigated and non-irrigated treatment (Figures 2.18 and 2.19).

At the narrow row spacings, the 23RS and 50RS treatments, there was a similar decrease in profile SWC within the irrigation treatments until 95 DAS, regardless of distance from the seed row (Figures 2.18 and 2.19). During the next measurement interval, between 96 and 110 DAS, 48 mm of rainfall occurred. The non-irrigated treatments had the greatest increase in profile SWC after these rainfall events for both row spacing treatments, 20.6 to 28.1 mm, whereas in the pre-season irrigated treatments the increase to SWC was only 6.7 to 15.3 mm. Pre-season irrigation increased the early plant growth of the chickpea plants at both row spacings due to the higher initial profile SWC. As a consequence, the greater crop biomass led to the chickpea plants using more of the water made available from rainfall during subsequent plant growth than occurred in the non-irrigated treatments. Evidence of the continued greater crop water use in the pre-season irrigated over the non-irrigated treatments was the greater loss of profile SWC from 110 to 124 DAS in the 50RS and the greater increase in profile SWC of the non-irrigated treatment with rainfall later in the season (Figures 2.18 and 2.19).

The wide row spacing of 75 cm had a different pattern of water use than the narrower row spacing treatments, which reflects the lower early biomass production which led to lower final yields (Figure 2.20). The high profile SWC at 12 cm from the seed row on 75 DAS indicates that there was available water for chickpea growth early in the season, whilst the plant biomass remained lower than the 23RS and 50RS treatments during this period. The within-row competition of seedlings for available light, nutrients and water early in the season may have resulted in smaller plants and root systems which could not access the soil water further from
the seed row (Jettner et al. 1999; Riethmuller and MacLeod 2001). The combination of low plant population density but high within-row plant population may be an additional factor that has led to decreased uptake of soil water. Later in the season, growth in the 75RS treatment did recover, in that plant biomass and final yields were similar to that of the 50RS treatment.

The actual profile SWC of the pre-season irrigated and non-irrigated, 75RS treatments were within the range of profile SWC in the narrower row spacings at the start of the monitoring period (Figures 2.18 to 2.20). However, in comparison to the narrower row spacing treatments, in the 75RS treatments there was no difference between the profile SWC of the pre-season irrigated and non-irrigated treatments at 12 and 25 cm from the seed row. In addition the profile SWC in the non-irrigated treatments was within the range reported for the pre-season irrigated, 23RS and 50RS treatments. In the middle of the row at 37 cm the profile SWC followed a similar trend to profiles monitored at the narrower row spacings, with greater profile SWC in the pre-season irrigated treatments early in the season, and less profile SWC later in the season when compared to the non-irrigated treatments. The low plant density of 24 plants/m\(^2\) can account for low crop biomass and decreased water use by the crop in the 75RS treatment. The lower profile SWC further from the seed row early in the season were likely to be a result of surface soil evaporation rather than plant water use as the lack of canopy cover extending between rows and less root penetration between rows left a bare inter-row soil surface in the 75RS treatment.

When the profile SWC is compared to the CLL (283 mm/m) and estimated wilting point (267 mm/m), and interpreted in conjunction with the LWP (Figure 2.16), periods of water limitation to crop growth may be identified. When the profile SWC was close to the CLL, the plants were under greater stress as indicated by low LWP (124 DAS), whilst when the plants were at profile SWC greater than the CLL, the corresponding LWP did not indicate crop water stress (111 DAS). Using the CLL as a guide, the plants in the 23RS (Figure 2.18) and 50RS (Figure 2.19) non-irrigated treatments were often below the CLL during early crop growth, which may explain the low early biomass production of these treatments in comparison to the pre-season irrigated treatments which were growing at profile SWC above the CLL. During the chickpea crops early growth in the 75RS treatment, in both irrigation treatments, the profile
SWC (Figure 2.20) was greater than the CLL towards the middle of the row, and at 12 cm from the seed row the profile SWC was well above the CLL. This may indicate that after emergence the chickpea plants in the 75RS treatments were not under water stress early, and the lower initial PPD was the limiting factor to early biomass production rather than crop water stress. From 141 DAS, the plants started to senesce when the total soil water content in the profile SWC of all treatments remained closer to the CLL rather than the estimated wilting point. Closest to the seed row (12 cm), values of profile SWC were 286 to 291 mm/m in the pre-season irrigated treatments. The 50RS and 75RS treatments had 306 and 322 mm/m in the non-irrigated treatments, respectively. The high values in profile SWC in the non-irrigated treatments of the 50RS and 75RS treatments show soil water was still available in the profile, and factors other than profile SWC during reproductive growth limited crop growth in these treatments.

Depth of root growth also has an impact on plant extraction of available water. Measurements of root growth were not taken in this experiment due to the high clay content of the soil, the dry soil profile and the logistical difficulties of sampling across the rows, due to the nature of the row spacing experiment. Instead, the change in soil water content at each 10 cm increment in the soil profile can be used as an indicator of water uptake by plant roots at that depth (Siddique and Sedgely 1987) (Figures 2.21 to 2.23). Depth of extraction of water by chickpea in a similar soil type at Merredin has been reported from 40-80 cm (Leport et al. 1998; Leport et al. 1999) and roots found to a depth of 100 cm although most root growth was concentrated at 0-40 cm depth (Siddique and Sedgley 1987). It has been suggested that deep rooting in this soil type is unlikely due to the dense subsoil clay layer which limits root penetration (Siddique et al. 2001). In the 2008 study, the differences in profile SWC and the increased plant biomass from the pre-season irrigated treatments compared to the non-irrigated treatments suggests that these treatments accessed soil water differently. The changes to soil water content with each 10 cm depth, were shallower in the pre-season irrigated (40 cm depth) compared to the non-irrigated treatments (70 cm depth). This was the case for the 25RS and 50RS treatments at all distances from the seed row (Figures 2.21 to 2.22). Whilst there were no actual measurements for root growth in this experiment, this suggests different patterns of root
growth between the pre-season irrigated treatments compared to the non-irrigated treatments. Any additional root elongation and water uptake within the shallow depths in the pre-season irrigation treatment may also increase the uptake of nutrients by plants within these treatments.

After the initial rainfall events to 110 DAS, in both the 23RS and 50RS treatments, there was an increase in water storage to 70 cm depth in the non-irrigated profile, whereas in the pre-season irrigated profile any change in soil water was recorded to only 40 cm depth (Figures 2.21 and 2.22). This difference in response to rainfall could indicate that in the pre-season irrigated treatment plant roots have intercepted water applied as rainfall, before it could infiltrate deeper into the soil profile. Liu et al. (2011) found that where soil water conditions are high, chickpea plants were found to have longer roots with larger surface area in the 0-40 cm depth than in low water conditions. The increased early plant growth of the pre-season irrigated treatment and the lack of change in soil water content to depth (<50 cm) may indicate that there were more plant roots at the shallow depth in the pre-season irrigated treatments due to adequate soil water in the upper profile early in the season. In comparison the non-irrigated treatments had less profile soil water early in the season and consequently crop growth was limited. Chickpea plants are able to respond to dryer conditions in the soil by growing roots deeper into the soil profile (Benjamin and Nielsen 2006). However, in the non-irrigated treatments of the 2008 experiment there is no evidence of this root behaviour as although there were changes to soil water content to depth (70 cm), indicating soil water recharge from rainfall, there is no indication of subsequent crop use of the extra water at these depths.

In the 75RS treatment, with 10 cm depth increments there were greater changes in soil water content in the shallow depths (to 50 cm) in the pre-season irrigated profile compared to the non-irrigated profile at 12 cm from the seed row (Figure 2.23). The non-irrigated profile had smaller changes to soil water content at the shallow depths and also to 90 cm depth in the profile. The pre-season irrigated and non-irrigated profiles both show evidence of changes in water content at depth at both the 25 and 37 cm distances from the seed row. The changes in soil water content occur deeper in the profile of the 75RS treatment in comparison to the narrower row spacing treatments, and later in the season the 75RS non-irrigated treatment had high profile SWC when the other row spacing and distances from the row are considered. Whilst it is still
possible that root growth extended deeper into the profile to access water in the non-irrigated profile, the continued gradual increase in profile SWC may indicate that the lower plant density of the 75RS treatments have not used the available profile SWC, allowing some recharge of soil water to depth.

2.4.3 Evapotranspiration

Total evapotranspiration was greater in the pre-season irrigated than the non-irrigated treatments (Figure 2.24). Within the non-irrigated treatment, total ET decreased with increasing row spacing at 12 cm from the seed row. The lower plant population and much lower crop biomass in the 75RS treatment would have meant there was less of a requirement by plants for water than in the 23RS and 50RS treatments. The ET$_{cum}$ coupled with the crop biomass data may give some indication of the partitioning of soil water between soil evaporation and crop transpiration. Cumulative evapotranspiration curves of the 23RS and 50RS treatments have similar patterns of water loss (Figures 2.25 and 2.26). There was greater water loss through ET in the non-irrigated treatments until 96 DAS, after which the pre-season irrigated treatments had greater ET$_{cum}$. In the 75RS treatments, the pre-season irrigated treatments had the greater ET$_{cum}$, and the difference in ET$_{cum}$ between irrigation treatments decreased with distance from the seed row, until at the middle of the seed row (37 cm) there was no difference between ET$_{cum}$ of the irrigation treatments until 110 DAS (Figure 2.27).

The patterns of water loss are explained by the early chickpea biomass and canopy cover across the rows in each treatment. Early chickpea crop establishment can reduce evaporation from the soil surface, with soil evaporation occurring mostly early in the season when ground cover by the crop is low (Zhang et al. 2000). In environments such as south-west WA, early growth and rapid ground cover has been found to be an advantage for chickpea production (Siddique et al. 2001). Under rainfed conditions, the percentage of water loss due to soil evaporation in a chickpea crop was 56 to 62 % of ET (Siddique and Sedgley 1987), while in wheat at the same site soil evaporation was reported to be approximately 40 % of ET early in the season (Siddique et al. 1990), and in faba beans, sown late in the season, soil evaporation was 54 % of ET (French 2010). In a chickpea crop sown in south-east Queensland, evaporation
was 55 % of total water use (PPD 25 plants/m² and RS 17 to 20 cm) (Thomas and Fukai 1995b). In 23RS and 50RS treatments, the pre-season irrigated treatments had greater early crop growth (Figure 2.12) which means they had better canopy cover and greater interception of light by leaves. This in turn increases crop photosynthesis and continued crop growth in the pre-season irrigated plot. By contrast the greater exposure of the bare surface soil due to less crop biomass and canopy cover in the non-irrigated crop led to a greater proportion of water loss as soil evaporation. Similarly the lack of difference in ETcum with distance from the seed row in the 75RS treatments may be attributed to soil evaporation as the main effect on water loss from the inter-row rather than plant transpiration, as crop biomass was low early in the season and canopy cover would not have reached the middle of the row. This suggests that towards the middle of the row soil water supply for evaporation was similar for the pre-season irrigated and non-irrigated treatments.

Later in the growing season (from 96 or 110 DAS), the ETcum was greater in the pre-season irrigated treatments for all row spacing treatments, notwithstanding increased rates of ET after significant rainfall events (48 mm before 110 DAS and 30 mm before 141 DAS). The period of pod development, between 110 to 125 DAS, coincided with greater water use as reflected in the rate of ETcum in the pre-season irrigated plots. During this time, the greater water use contributed to the greater number of pods developed on chickpea plants in the pre-season irrigated treatments (Figure 2.13).

2.4.4 Crop water stress

In the rainfed environment of south-west WA, chickpea crops are often exposed to terminal drought during pod set and seed filling due to limited rainfall (Leport et al. 1999). As profile SWC decreases along with soil matric potential, LWP must also decrease to continue the flow of water from the soil through the plant via a water potential gradient (Larcher 2001). In this experiment, the chickpea crop relied on rainfall to replenish soil water deficits. Leaf water potential at the initiation of pod formation coincided with a considerable addition of water from rainfall (37 mm) in the previous 20 days. Profile SWC was high (> CLL) in all treatments and LWP was close to -1 MPa (Figure 2.16) which was within the range of LWP reported by
Leport *et al.* (1999; 2006) where photosynthetic rate and stomatal conductance are not affected by water stress. This indicates that the chickpea crops were not exposed to water stress at the critical pod formation stage. Moreover, pre-dawn LWP did show signs of recovery overnight. The recovery in LWP is important as even small water deficits can accumulate and lead to water stress (Larcher 2001). A second measurement of LWP occurred at pod-filling. Rainfall in the previous 24 days was limited (2.5 mm), and as a consequence profile SWC had dropped across all treatments except the non-irrigated 75RS (Figure 2.20). The midday LWP for all treatments was below -3 MPa, indicating the chickpea plants were under water stress (Siddique and Sedgley 1987; Leport *et al.* 1999; Leport *et al.* 2006). Whilst the onset of crop water stress across the treatments was not determined, the similarities in LWP between treatments at both times of measurement indicate that all treatments were under comparable conditions of water stress during the season. However, the processes that led to water stress may have been different between treatments. Any advantage of the pre-season irrigation was lost by 110 DAS, with profile SWC (124 DAS) close to the CLL. In addition, the greater crop biomass of the pre-season irrigated, narrow row spacing treatments was consistent with research that found larger plants develop water deficits and water stress faster than smaller plants (Leport *et al.* 2006). In the non-irrigated treatments, there was soil water in the profile at 124 DAS, however values of LWP still indicated crop water stress implying the soil water in the profiles was unavailable to the plants. In other experiments where chickpea plants were under water stress and there was unused soil water remaining in the soil profile, this was attributed to limited early chickpea growth and slow uptake of water by the chickpea during the season (Thomas and Fukai 1995a; Thomas *et al.* 1995). Leaf water potential values of -3 to -3.6 MPa have been reported in this region during pod development (Leport *et al.* 1998; Leport *et al.* 1999). At these levels the net photosynthetic rate was likely to be low but remain positive. This ensures energy was still available to translocate carbon and nitrogen from stems, leaves and shoots to the developing seed (Leport *et al.* 1998).

In 2008, between the midday and pre-dawn measurements of LWP at 124 DAS, there was 5 mm of overnight rainfall. This enabled the plants to temporarily recover to LWP levels which indicate no plant water stress. However, there was no follow up rainfall and the 5 mm did not
increase the reserves of soil water, so it is most likely the chickpea plants would return to a water stressed state. This is supported by previous work in chickpea during the pod-filling period at Merredin where 28 mm of rainfall was required for the LWP to increase from -3 to -2 MPa (Leport et al. 1999). Water stress during the reproductive stage of crop growth leads to a reduction in pod and seed numbers due to a decrease in the formation of new pods after the onset of stress and to pod abortion (Thomas and Fukai 1995a; Behboudian et al. 2001; Leport et al. 2006; Fang et al. 2010). Fang et al. (2010) also reported that the onset of water stress decreased the production of flowers and induced flower abortion, with the function of the pistil/style being more affected than the pollen of a water-stressed plant. Earlier onset of water stress at flowering in comparison to pod setting will lead to a greater decline in grain yield (Tesfaye et al. 2006). Whilst there are indications of crop water stress to all treatments only the pre-season irrigated, 50RS treatment showed greater potential for seed yield early in the season than eventuated, and a mean loss in pod weight from 125 DAS to 141 DAS even though biomass and pod weights early in the season were comparable to the pre-season irrigated 23RS treatment.

2.4.5 Water use efficiency

Values of water use efficiency for chickpea GWUE and WUE are similar to values reported by other researchers in south-west WA (Table 2.7) (Siddique and Sedgley 1987; Siddique et al. 2001). Values in the 2008 trial were between 4.9 and 6.7 kg/ha/mm for GWUE and 12.8 to 15.7 kg/ha/mm for WUE. The values of GWUE and WUE across WA have been reported to range from 2.6 to 6.8 kg/ha/mm and 11 to 35 kg/ha/mm, respectively (Siddique and Sedgley 1987; Siddique et al. 2001). For similar sowing dates at Merredin to the present experiment, GWUE of 5 kg/ha/mm and WUE of 16 to 21 kg/ha/mm have been reported (Siddique and Sedgley 1987). Siddique and Sedgley (1987) also reported that whilst the WUE varied among years and with variation in rainfall, the GWUE remained stable. In this present study, GWUE was not different between row spacing treatments but did vary with irrigation treatments, while the WUE response to row spacing varied with irrigation.
With pre-season irrigation more crop biomass was produced per millimetre of water in the 23RS treatment than the 75RS treatment. The lower biomass produced per millimetre of water, may be another indicator of PPD limiting final yield in the 75RS treatments. In the 75RS treatment the chickpea plants were at very low PPD, morphological plasticity enabled each plant to compensate for low PPD and produce more biomass and grain to reach final yields and WUE similar to the 50RS treatment but not to that of the 23RS treatment. In a chickpea time of sowing trial, Siddique and Sedgley (1987) concluded that water use by the crop depends on soil cover which is controlled by canopy development and interacts with soil water availability and phenological development. Similarly in this experiment which examined effects of row spacing, greater accumulated biomass and therefore canopy development has resulted in greater WUE.

2.5 Conclusion

Extra water in the soil profile at sowing produced greater early biomass and final grain yields of chickpea. Even 20 mm extra stored soil water at sowing was sufficient to produce significant increases in final yields. Pre-season rainfall that totals >75 mm may be enough to achieve such gains in grain yield. The additional stored water increased crop yields through improved early biomass production, even though the extra soil water was already depleted at pod formation and pod-filling. The chickpea plants were able to utilise the available soil water in the pre-season irrigated profile better than the non-irrigated treatments, possibly through greater root growth in the surface 40 cm of the soil profile. The effect of row spacing on grain yield was not altered with pre-season irrigation, indicating that growing season rainfall was the key determinant of factors that lead to chickpea performance in narrow or wide rows. Under high yield potential (2008), chickpea sown at narrower row spacing achieved higher grain yields than at wider row spacing. Under low yield potential (2007), grain yield increased with increases in row spacing to 75 cm.

The irrigation and row spacing treatments had different patterns of crop growth and water use through the season and this was attributed to the PPD. During the 2008 season, which had high yield potential, the patterns of water use by the chickpea crop were affected by between
and within-row spacing plant configurations which affected plant-to-plant competition for water and resources. Planting configurations resulted in more plants within the seed row at wide row spacing, but lower overall PPD. Early in the season the chickpea plants in the two irrigation treatments at the wider row spacing showed no difference in either biomass production or soil water content. Differences in plant biomass and yield became evident at maturity between irrigation treatments at wide row spacing, indicating that chickpea plants in greater initial profile soil water condition were better able to utilise plant available water at the end of the growing season. Later in the season soil water content was high within the soil profile for wide row spacing without the pre-season irrigation but plants did not utilise this water for growth. This suggests that the soil water was below (vertically) and outside (horizontally) the root zone and therefore unavailable to plant growth.

In the narrower row spacing treatments the differences in biomass production between irrigation treatments were significant during early growth. Similar rates of growth by chickpea plants occurred in the 23RS and 50RS treatments with pre-season irrigation early in the season; however the plants in the 50RS treatment experienced a loss of pod numbers and pod weight later in the season leading to grain yields less than potential. In the 23RS and 50RS treatments, crops with high PPD and without pre-season irrigation were exposed to soil water conditions close to the CLL during early crop growth which decreased early biomass production compared to the pre-season irrigated treatments.

The differences in soil water uptake and biomass production early in the season established whether the crop would be stressed later in the season at pod formation and filling. The ET rate increased at pod development in the pre-irrigated chickpea plants compared to the non-irrigated chickpea but all treatments were at similar levels of water stress during pod-filling. The water stress developed at pod-filling occurred via different pathways for each irrigation treatment. In the case of the non-irrigated plots in the 50RS and 75RS treatments, soil water was available in the profile but not utilised leading to crop water stress, and in the case of the pre-season irrigated profiles (all RS) the profile soil water content was close to the estimated crop lower limit, leading to crop water stress.
The results of this work may also provide an indication of the response of chickpea yields to different row spacing configurations in the HBT of Bangladesh where profile soil water content is high at sowing, and within-season rainfall is required to ensure adequate soil water reserves to keep plants from reaching water stress. The introduction of minimum tillage techniques means the sowing rate and row spacing needs to be re-assessed for this environment. The soil profile is potentially full of water at sowing and dries with continued crop water use. It is important to know how the arrangement of plants, both by row spacing and plant density within-rows, will delay the onset of drought stress. This work in south-west WA has shown that even when initial profile SWC is high, the yield response to row spacing configuration is linked to achieving non-limiting profile SWC throughout the season. This means within-season rainfall is also required to ensure adequate soil water reserves to keep plants from reaching water stress. As will be shown in the following chapters the rainfall during the chickpea growing period in the HBT of Bangladesh is minimal therefore a wider row spacing configuration may be best for the low yield potential offered by in-season rainfall.
3 Soil physical conditions that limit chickpea emergence with
particular reference to soils of the High Barind Tract of Bangladesh

3.1 Introduction

Chickpea crops in the rice and rice-wheat cropping systems of South Asia are grown mainly on residual soil water after rainy season rice and are subject to a range of stresses which may result in poor germination, emergence and stand establishment (Johansen et al. 2008b; Waddington et al. 2009). After harvest of the rice crop, the region of the HBT of Bangladesh has high evaporation rates and high temperatures that result in rapid loss of surface soil water, even though subsurface layers retain high soil water content (Musa et al. 2001). This results in sub-optimal surface soil water conditions for germination and emergence of chickpea. In this agro-ecosystem, it is important that chickpea seeds germinate and emerge quickly before the surface soil dries, such that a vigorous root system develops to support adequate nodulation and access to stored soil water at depth in order to cope with terminal drought (Johansen et al. 1997; Harris et al. 1999; Waddington et al. 2009). In addition to limiting surface soil water conditions, crop establishment can also be hampered by hard setting soils, poor quality seed and sowing under sub-optimal conditions due to scarcity of labour or delays to sowing a crop with traditional broadcast systems using bullock-drawn technology (Harris et al. 2005; Johansen et al. 2008a).

Surface soils (0-15 cm) in the HBT have a silty clay texture and bulk densities between 1.4 and 1.6 g/cm³ (Ali 2000) and are often described as hard setting clay soils. At 10-12 cm depth, there is usually a clay plough pan layer, a result of the previous history of paddy rice cultivation (Haque et al. 2010). These characteristics of soil in the HBT lead to a seed-bed which is not conducive for chickpea germination or emergence in combination with an environment which quickly dries the surface soil during the period that is optimal for planting.

In addition to soil physical constraints inherent in HBT soil, the development of new minimum tillage techniques adds another dimension to the management of these soils during the sowing of chickpea. The strip tillage (ST), zero tillage (ZT) and single pass shallow tillage (SPST) methods produce seed-beds which result in altered soil strength, aggregate size and bulk
density compared to conventional tillage and sowing methods (Hossain et al. 2009; Haque et al. 2010). The soil physical conditions of the disturbed soil in the seed furrow may limit the emergence of the seed: if there is inadequate seed coverage by the soil, if the soil covering the seed is not of an appropriate tilth, if the seed is not sown at the appropriate depth into the moist zone, and if the soil is too wet during tillage, creating smearing on the base of sides of the furrow. One or more of these conditions may lead to accelerated drying of the seed-bed soil, poor seed-soil contact and increased strength of soil through which the radicle and plumule must penetrate.

The soil physical conditions of aeration, temperature, water content and strength affect the germination and emergence of a seed (Cardwell 1984). These soil physical conditions are dependent on properties such as particle size distribution and bulk density which influence pore size distribution and aggregate size. These properties, in turn, provide a seed-bed that either promotes or limits seed germination and seedling emergence (Atkinson et al. 2007). Ten percent of pores should be air-filled to ensure there is enough oxygen to support respiration and metabolic activity of the developing seed (Dexter 1988; Hadas 2004). Temperatures between 20 and 29 °C are optimum for chickpea emergence (Soltani et al. 2006).

The seed water potential, soil water potential (ψ) and the seed-soil interface are important factors in the initial water uptake phase required for seed germination (Hadas 2004). The period from germination to emergence, when the seeds continue to require water and oxygen, and utilize their seed reserves for nutrients (Baker 2007b), may be the critical period for successful chickpea emergence in soils experiencing accelerated drying of the surface soil.

Previous research has determined the soil water contents at which emergence of chickpea seedlings can become limited. The range in gravimetric soil water contents (θg) at which chickpea emerged was wide, from 9 to 34 %, and emergence was delayed and declined with soil drying (ICRISAT 1981; Saxena et al. 1983; Sharma 1985; Johansen et al. 1997; Hosseini et al. 2009a). As soil water content decreases, differences in water potential between soil and seed decline such that imbibition ceases and germination is no longer possible (Collis-George and Sands 1959; Dasberg and Mendel 1971). A chickpea seed must have a weight gain of 72 to 75 % of the dry seed weight to obtain the critical hydration level required for germination to
proceed (Hadas and Stibbe 1973). Researchers have reported that the rate of chickpea germination decreased as external $\psi$ decreased from 0 to -750 kPa, and was not possible at -1000 kPa (Singh and Afria 1985) whilst emergence tolerated $\psi$ only as low as -500 kPa (Sharma 1985). Even at optimum $\psi$ for germination, decreased hydraulic conductivity and reduced seed-soil contact can alter uptake of water and delay germination (Hadas and Russo 1974; Hadas 1977).

On-farm seed priming, the process of soaking seed in water for 6 to 10 hours, surface drying and then sowing within the day has been adopted to improve chickpea seedling emergence in the HBT (Musa et al. 2001). This means the seed is sown in a hydrated state (Murungu et al. 2004). Priming of chickpea has been found to hasten germination and improve plant stand and yield (Musa et al. 2001; Rashid et al. 2004; Harris et al. 2005). Additional studies with chickpea and other crops have found improved resistance to diseases with priming and improved nodulation from native rhizobia and when *Rhizobium* inoculation was included in the priming water (Musa et al. 2001; Harris et al. 2005). The benefits of priming which are associated with increased resistance to disease were hypothesised to be increased vigour of the plant (health), faster development of the plant (escape) or through the responses invoked in the seed under conditions of rapid imbibition which allow the seedlings to have continued resistance to stress (Systemic Acquired Resistance, SAR)(Rashid et al. 2004). Seed priming has been identified as a technology easily implemented, with low risk and clear benefits (Murungu et al. 2004; Harris et al. 2005).

Knowledge of the optimal range of each of the soil physical properties (soil water content, soil strength, bulk density and aggregate size) required during the establishment period of chickpea in a hard setting soil representative of the HBT of Bangladesh is needed to allow the seed-bed properties after mechanised row-sowing to be matched to chickpea requirements. The objectives of the study were:

1. to identify the soil water contents and soil water potential required for emergence of chickpea plants;
2. to determine the limitations to chickpea emergence with increasing bulk density and soil strength; and
3. to determine the extent to which chickpea emergence is limited by different above-
seed or below-seed soil physical conditions.

3.2 Materials and Methods

Seven laboratory experiments were conducted: five investigated the germination and emergence of chickpea at different water contents, and two investigated chickpea emergence under different soil bulk density and aggregate size.

3.2.1 Soil

Three different soil types were used in these laboratory experiments. Two were surface soils (0-10 cm) from Merredin, Western Australia (Australian soil classification, Calcic Red Dermosol, (Isbell 1996)) collected about 500 m apart. The two soils from Merredin were the same soil type and had very similar physical properties (Table 3.1). Merredin 1 was collected from the location of the field site in 2007 (Chapter 2), logistically this was not possible when more soil was required in 2008 so soil was sourced from the location 500 m away. The third soil was a surface soil (0-20 cm) collected from Kantopasha Village, Godagari Upazilla, Rajshahi District in the HBT of Bangladesh (USDA Soil Taxonomy, Aeric Haplaquept (Catling 1992; Brammer 1996). The particle size distribution and bulk density of these surface soils are presented in Table 3.1. All soils were air-dried and passed through a 4 mm sieve before use.

The Merredin soil was used as a surrogate for the HBT soils due to the lack of controlled environment facilities in Rajshahi, Bangladesh to complete experiments and the difficulty of importing large volumes of HBT soil to Australia. The Merredin soil was similar to the HBT soil in clay percentage, higher in proportion of sand and in bulk density, however the percentage of silt was lower. Experiments 1 to 3 were conducted using surface soil from Merredin 1, Experiments 6 and 7 using soil from Merredin 2 and Experiments 4 and 5 using the soil from Bangladesh. Experiments 1 to 4, 6 and 7 were carried out at Murdoch University, WA; Experiment 5 was completed in Rajshahi, Bangladesh.
Table 3.1. The particle size distribution and bulk density of the Merredin and Bangladesh soil types.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Sand (%)</th>
<th>Particle Size</th>
<th>Clay (%)</th>
<th>Bulk density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merredin 1</td>
<td>61</td>
<td>10</td>
<td>29</td>
<td>1.6</td>
</tr>
<tr>
<td>Merredin 2</td>
<td>64</td>
<td>11</td>
<td>25</td>
<td>1.6</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>48</td>
<td>24</td>
<td>28</td>
<td>1.4</td>
</tr>
</tbody>
</table>

3.2.2 Seed

Seeds of desi chickpea were used in all experiments: cv. Genesis 836 was used in Experiments 1 to 4, 6 and 7, and cv. BARI Chola 5 in Experiment 5. Seeds were selected for uniformity of size in each experiment.

3.2.3 Definitions of germination and emergence

At harvest, seeds were inspected to determine if germination had occurred (radicle >2 mm in length), and if so, root and shoot length were measured and total mass of the seedling taken. If the seed had not germinated, it was placed in a petri dish on moist filter paper to determine viability of the seed by assessing its capacity to germinate. Seedlings were classed as emerged when they were first visible on the soil surface. When the shoot emerged, the seedling was removed from the pot and destructively sampled. Root length and shoot length were measured using a rule with half millimetre graduations. Roots were separated into main and lateral roots as appropriate.

3.2.4 Germination and emergence of chickpea at different water contents.

3.2.4.1 Experiment 1

Experiment 1 was conducted to determine the soil water content at which chickpea germination is limited. Five treatments of soil water content were between 13 and 28 % by weight. Soil was wet-up to the treatment water contents and mixed before being left in a sealed container to equilibrate for 48 hours. There were 18 replications of each treatment. Half the soil was placed before eight seeds were evenly sown across a petri dish (1 cm deep, 8 cm diameter) then the other half of the soil (1 cm) was placed on the top of the seeds, the bulk
density of the soil above and below the seed was 1.3 g/cm³. The petri dishes were sealed and placed in a growth cabinet at 25 °C. On days 3, 6, 7, 10, 11 and 12, three replications of each treatment were removed and destructively sampled.

3.2.4.2 Experiment 2

To better understand the rate of emergence of seedlings under the different soil water contents, an experiment was conducted to count seedling emergence. The soil was wet-up to the initial soil water contents of 14 to 21 % by weight. One hundred and eight chickpea seeds were sown in a 3 x 3 cm grid pattern in containers of dimensions 39 x 29 cm. Containers were 12 cm deep and seeds were sown at 3 cm depth. Containers were covered with a lid that was not airtight but prevented excess evaporation and allowed entry of light. They were placed in a growth cabinet at 20 °C, and 12 hour day/night. At each treatment soil water content (14, 15, 18 and 21 % by weight). Two replicate containers were sown for each soil water content treatment. Emergence was checked daily when emerged seeds were marked and counted. Ten days after sowing, the experiment was stopped and all seeds counted as emerged, germinated or not-germinated.

3.2.4.3 Experiment 3

Experiment 3 was conducted to determine how soil water content affected emergence rate and root and shoot properties of the chickpea seedlings. There were eight soil water content treatments within the range of 3 to 27 % by weight with eight replications. Soil was placed into square pots 18 cm high and 9 cm wide. Soil was placed into the pots at a bulk density of 1.3 g/cm³, calculated by the mass of soil in the volume of the pot, filled to a predetermined height. However, soil water contents of 0, 5, 20 and 25 % all settled to below this height resulting in bulk densities of 1.6, 1.4, 1.6 and 1.8 g/cm³, respectively. One seed was sown per pot at 3 cm depth. The pot was placed in a sun-bag (Sigma-Aldrich) and the sealed bag placed in a growth cabinet at 25 °C and 12 hours day/night. Sun-bags are 44 x 20.5 cm, gusseted transparent bags, with a 24 mm diameter, 0.02 µm pore filter on one side. The bags were folded at the top to prevent evaporation; air exchange is then possible through the filter. After sowing,
the pots were monitored daily to determine if seedlings had emerged. Twelve days after sowing all remaining pots were removed and destructively sampled.

3.2.4.4 Experiment 4 and 5

Experiments 4 and 5 were conducted to determine the soil water content at which chickpea emergence was limited in a soil typical of the HBT in Bangladesh. In Experiment 4, carried out at Murdoch University, six soil water content treatments were between 12 and 23 % by weight, with eight replications. Soil was placed into cylindrical pots 6 cm high and 4 cm in diameter. Soil was placed into the pots at a bulk density of 1.3 g/cm³. One seed was sown per pot at 3 cm depth. The pots were placed in sun-bags and put in a growth cabinet at 20 °C and 12 hours day/night. After sowing the pots were monitored daily to determine if seedlings had emerged. Experiment 5 was conducted in Rajshahi, Bangladesh to further investigate how the soil water content of HBT soil limits chickpea emergence. Pots were 12 cm high, 6.5 cm diameter and the seed sown at 3 cm depth in soil 9.5 cm deep. The experiment had two factors, factor one consisted of seven treatments of soil water content, between 2 and 27 % by weight. Factor two consisted of two seed treatments of primed seed or non-primed seed. There were ten replications of each treatment combination. Pots were placed in plastic bags and sealed with elastic bands to prevent evaporation. The pots were placed under shade in ambient conditions: daylight hours were between 7:30 am and 6:15 pm, and daily mean minimum and mean maximum temperatures for the period were 14 and 25 °C, respectively. After sowing the pots were monitored daily to determine if seedlings had emerged.

3.2.5 Emergence of chickpea at different soil bulk densities and aggregate size distribution

In Experiments 6 and 7, after pre-wetting, soil was placed in cylindrical PVC pots 15 cm high and 8 cm in diameter. The PVC pots consisted of a separate base (12 cm high) and top (3 cm high) to allow creation of different soil physical properties above and below the sown seed (Figure 3.1). One seed was sown per pot at 3 cm depth.
3.2.5.1 Experiment 6

Chickpea seeds were sown into PVC pots with soil at different bulk densities and constant soil water content. The <4 mm soil was wet-up to the initial soil water contents of 13 % (w/w) and mixed before being left in a sealed container to equilibrate for 48 hours. Seven soil bulk density treatments were at 0.1 g/cm³ intervals from 1.3 to 1.9 g/cm³ (above which compaction was no longer possible).

To construct the soil cores, the soil was placed in 3 cm increments. To uniformly compact soil, layers of calculated mass of soil were compacted to a height required for each bulk density. A bench-mounted hand press was used with a circular disc modification to compress the entire surface area of the core.

Soil strength of the compacted soil was measured using a penetrometer. Penetrometer resistance \( (Q_p) \) was measured on the surface of the top layer with a steel needle with a cone diameter \( (d_p) \) of 2 mm and an angle of 30°. The needle was attached to a force gauge (Dillon AFG 500 N), on a loading frame. The tip was inserted at two locations in the core surface to 6 mm. The force \( (F) \) at the probe tip was measured in newtons and converted to penetrometer resistance in MPa calculated from (Materechera et al. 1991):

\[
Q_p = \frac{4F}{\pi d_p^2}
\]
The pot was placed in a sun-bag (Sigma-Aldrich) and the sealed bag placed in a growth cabinet at 21 ºC and day/night of 12 hours. Gravimetric soil water contents were determined for each treatment at sowing and at harvest. Eight days after sowing when no shoots had emerged from the soil surface, all pots were removed from the growth cabinet and destructively sampled. The top 3 cm layer of soil had dried significantly. Instead of penetrating through the core, the germinated seedlings pushed up the whole 3 cm layer and attempted to emerge through the gap between the top and the base soil layers. Seeds were inspected to determine if germination had occurred (radicle >2 mm in length), and if so, root length, shoot length and seedling weight were measured.

3.2.5.2 Experiment 7

There were five treatment combinations used to investigate the germination and emergence of chickpea seeds sown to simulate the soil physical conditions under strip tillage or full rotary tillage. The conditions were set to mimic different below-seed bulk density and above-seed soil tilth. Different soil tilth was simulated by three surface soil treatments: <4 mm aggregates, <2 mm aggregates, and >4 mm aggregates. Different below-seed soil bulk density was simulated by two treatments: soil compacted to 1.3 or 1.8 g/cm³. The schedule of five treatment combinations is shown in Table 3.2. There were ten replicates of each treatment combination.

Samples of <4 mm soil aggregates and >4 mm soil aggregates were wet-up to the initial soil water contents of 14 % (w/w) and mixed before being left in a sealed container to equilibrate for 48 hours. The <2 mm soil aggregate treatment was created by pushing the wet <4 mm aggregate soil through a 2 mm sieve. At the time of potting, the $\theta_g$ of the >4 mm and <4 mm aggregate soil was 14 % while it was 10 % for the <2 mm aggregate soil. To create the base soil bulk density, the mass of wet soil required was compacted in 3 cm layers. The above-seed <2 and >4 mm aggregate layers were created by pouring 138 g of the wet soil into the 3 cm layer above the sown seed.

The pot was placed in a sun-bag (Sigma-Aldrich) and the sealed bag placed in a glasshouse at 21 ºC, day/night of 12 hours. Gravimetric soil water contents were determined for each treatment at sowing and at harvest. Seedlings were classed as emerged when they were first
visible on the soil surface. When the seedling emerged, the soil was removed and destructively sampled; root and shoot lengths were measured and total mass of the seedling taken. Fifteen days after sowing soil in all remaining pots were removed and destructively sampled. Seeds were inspected to determine if germination had occurred (radicle >2 mm in length), and if so root length, shoot length and seedling weight were measured.

Table 3.2. Schedule of treatment combinations used in Experiment 7 to test chickpea germination and emergence with different soil structure conditions. Top core refers to conditions above the seed while base core refers to physical conditions below the seed.

<table>
<thead>
<tr>
<th></th>
<th>Treatment 1</th>
<th>Treatment 2</th>
<th>Treatment 3</th>
<th>Treatment 4</th>
<th>Treatment 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top core</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil aggregates</td>
<td>&lt;4 mm</td>
<td>&lt;2 mm</td>
<td>&gt;4 mm</td>
<td>&lt;2 mm</td>
<td>&gt;4 mm</td>
</tr>
<tr>
<td>Gravimetric soil water content (%)</td>
<td>14</td>
<td>10</td>
<td>14</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Bulk density (g/cm³)</td>
<td>1.3</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>Base Core</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil aggregates</td>
<td>&lt;4 mm</td>
<td>&lt;4 mm</td>
<td>&lt;4 mm</td>
<td>&lt;4 mm</td>
<td>&lt;4 mm</td>
</tr>
<tr>
<td>Gravimetric soil water content (%)</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Bulk density (g/cm³)</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

3.2.6 Soil physical properties

In each experiment, \( \theta_c \) was determined for each treatment at sowing and at harvest. Soil water potential was measured at -100, -300 and -1500 kPa using ceramic suction plates under pressure in a chamber, whilst potentials of -1.3 and -10 kPa were determined using ceramic suction plates under suction created by a hanging column of water (Cresswell 2002). Gravimetric soil water content at field capacity (\( \theta_f \)) and wilting point (\( \theta_wp \)) were at water potentials of -10 and -1500 kPa, respectively. Gravimetric water contents were converted to volumetric water content (\( \theta_v \)) using the sample bulk density. Soil water release curves were
established for each soil type using RETC computer program (van Genuchten et al. 1991). The
equation from van Genuchten et al. (1991) was used to model the water release curve:

\[ \theta_v = \theta_r + \frac{(\theta_s - \theta_r)}{\{1 + (\alpha \psi)^n\}^m} \]

where \( \theta_v \) is the volumetric water content (m\(^3\)/m\(^3\)), \( \theta_r \) is the residual water content (m\(^3\)/m\(^3\)), \( \theta_s \) is
the saturated water content (m\(^3\)/m\(^3\)), \( \psi \) is the water potential (cm), and \( \alpha, n \) and \( m \) are constants
that affect the slope of the retention curve: \( \alpha \) approximates the inverse of the air-entry potential
of the water release curve and \( n \) and \( m \) are parameters that control the slope of the curve
(Reutenauer and Ambroise 1989). As in van Genuchten (1980), the Mualem model was used
and \( m \) restricted to be:

\[ m = 1 - \frac{1}{n} \]

RETC was used to fit the values of \( \theta_s, \theta_r, \alpha, n \) and \( m \) and the following equations used to
calculate \( \psi \) from a given \( \theta_v \) (van Genuchten et al. 1991):

\[ \psi = \frac{1}{\alpha} \left( \frac{S_e}{S_e} \right)^{\frac{1}{n}} - 1 \]

where \( S_e \) is the effective degree of saturation or the reduced water content, and:

\[ S_e = \frac{\theta_v - \theta_r}{\theta_s - \theta_r} \]

The gravimetric water content when air-filled porosity was at 10 % (\( \theta_{agf} \)) was estimated from:

\[ \theta_{agf} = \theta_s - 1 \]

where \( \theta_s \) was an estimated parameter from the water release curve generated from the van
Genuchten et al. (1991) model.

3.2.7 Statistical analysis

Where treatments had equal replicates, Analysis of Variance (ANOVA) was used. The least
significant difference (l.s.d.) at the 5 % level was used to show differences between means. The
effect of soil water content, bulk density and aggregate size on germination, emergence and
chickpea growth characteristics were analysed by Residual Maximum Likelihood (REML)
because of unequal replication of treatment combinations. Where REML was used, the
estimated means from the model and the average l.s.d. were reported. All analysis was carried out with GenStat v11.1 (VSN International Ltd, United Kingdom).

3.3 Results

3.3.1 Soil physical characteristics.

One water release curve was calculated for each soil type (Merredin or Bangladesh soil) from the relevant data (Figure 3.2). The parameters estimated from the RETC program were: (i) for the Bangladesh soil type, \( \theta_r = 0.1314 \, \text{m}^3/\text{m}^3 \), \( \theta_s = 0.5578 \, \text{m}^3/\text{m}^3 \), \( \alpha = 0.0052 \), \( n = 1.7071 \); and (ii) for the Merredin soil type were, \( \theta_r = 0.1295 \, \text{m}^3/\text{m}^3 \), \( \theta_s = 0.5710 \, \text{m}^3/\text{m}^3 \), \( \alpha = 0.0265 \); \( n = 1.4817 \).

![Figure 3.2. Fitted water release curve for the Merredin soil (---) and the Bangladesh soil (—). The soil water potentials (\( \psi \)) of field capacity (-10 kPa, —) and wilting point (-1500 kPa, —) are also shown. The water release curve was fitted from measured parameters of volumetric water content at each of the water potentials of -1.3, -10, -100, -300 and -1500 kPa using the RETC program and the equations from van Genuchten et al. (1991) shown in the text.](image-url)
3.3.2 Germination and emergence of chickpea at different water contents.

In Experiment 1, the actual $\theta_e$ at sowing of the five treatments were 13, 14, 18, 23 and 28 % (Table 3.3). Germination of chickpea seeds was 100 %, 3 days after sowing (DAS) at a $\theta_e$ of 18 %. With increasing $\theta_e$ from 13 to 18 % the time taken for germination to occur decreased. At the driest $\theta_e$ (13 %), the germination at 3 DAS was 45 %, and rose to 100 % at 11 DAS (Figure 3.3). As the $\theta_e$ at sowing increased to 23 and 28 %, the number of germinated seeds increased with DAS.

Table 3.3. The mean gravimetric soil water content ($\theta_{gr}$%) of each treatment at sowing in Experiment 1. Values are means of three replicates. The $\theta_e$ at field capacity ($\theta_{fc}$, -10 kPa) and wilting point ($\theta_{wp}$, -1500 kPa) were determined experimentally, while the soil water potentials ($\psi_s$ kPa) for each soil water treatment were calculated from the water release curve (Figure 3.2).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Gravimetric soil water content mean ± S.E. (%)</th>
<th>Soil water potential (kPa)</th>
<th>Proportion of field capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.6 ± 0.1</td>
<td>-162</td>
<td>49</td>
</tr>
<tr>
<td>2</td>
<td>13.8 ± 0.4</td>
<td>-99</td>
<td>53</td>
</tr>
<tr>
<td>3</td>
<td>18.4 ± 0.5</td>
<td>-28</td>
<td>72</td>
</tr>
<tr>
<td>4</td>
<td>22.8 ± 0.1</td>
<td>-13</td>
<td>88</td>
</tr>
<tr>
<td>5</td>
<td>27.7 ± 0.2</td>
<td>-6</td>
<td>107</td>
</tr>
<tr>
<td>Field capacity</td>
<td>26</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>Wilting point</td>
<td>10</td>
<td>-1500</td>
<td></td>
</tr>
</tbody>
</table>

Shoot development was also related to $\theta_e$ at sowing (Figure 3.3). At $\theta_e \geq 18$ %, germinated seeds showed first signs of shoot development at 6 DAS. The number of seeds which had developed a shoot decreased (67 down to 21 %) when $\theta_e$ at sowing increased from 18 to 28 %. With increasing DAS, the numbers of seeds with shoot development increased. At the dry $\theta_e$ of 14 %, even though germination was successful (>83 %), shoots developed in 33 % or less of seeds.
Figure 3.3. The germination and shoot production characteristics of chickpea seeds sown at water contents ranging from 13 to 28 % (w/w) in a Merredin sandy clay loam for Experiment 1.  a) Percentage germination of chickpea seeds 3 to 12 days after sowing (DAS).  b) The percentage of seeds which had a visible shoot at 3 to 12 days after sowing (DAS).  Error bars indicate 1 standard error of the mean where visible.

Field capacity ($\theta_{fc}$) was calculated to be 25.7 %, and wilting point ($\theta_{wp}$) 9.9 % which means treatments 1 to 4 are between $\theta_{fc}$ and $\theta_{wp}$ (Table 3.3). Soil water potential and $\theta_{g}$ decreased from the sowing to the final sample date (12 DAS) for all treatments (Figure 3.4 and Figure 3.5). When the germination percentage was maximum at 3 DAS, the $\psi$ was lower than $\psi$ for field capacity. In drying soil, with decreasing $\psi$, time to maximum germination increased to 6 and 11 DAS. In the wet soil, the $\psi$ was greater than field capacity and maximum germination was at 10 DAS. This could indicate that the seeds in the dryer treatments required more time at $\psi$ >- 99 kPa to absorb water needed to germinate, whilst the seeds in the wetter treatments, < -14 kPa $\psi$, may have been limited by aeration, requiring the soil to dry somewhat before germination could occur.
Figure 3.4. Mean gravimetric soil water content ($\theta_g$) during 12 days after sowing (DAS) when chickpea germination was monitored in Experiment 1. Treatments are the starting $\theta_g$ at sowing, which equates to the $\theta_g$ at 0 DAS. Error bars indicate 1 standard error of the mean where visible.

Figure 3.5. Mean soil water potential ($\psi$) during 12 days after sowing (DAS) when chickpea germination was monitored during Experiment 1. Where $\psi$ was greater than the residual water content ($\theta_r$) the highest calculated $\psi$ from the RETC analyses was inserted, -1.3 x 10^6 kPa. Treatments are the starting $\theta_g$ at sowing, which equates to the $\psi$ at 0 DAS. Error bars indicate 1 standard error of the mean where visible.

To determine the time it took for emergence of chickpea seedlings under different soil water contents, a bulk sowing experiment was conducted (Experiment 2). The emergence of seeds was monitored daily and the rate of emergence under four $\theta_g$ treatments determined (13.7 to 20.7 %, rounded to the nearest percent, Table 3.4). The $\theta_g$ of 15 % had the greatest number of emerged seeds followed by $\theta_g$ of 14 %. The $\theta_g$ of 18 and 21 % had fewer seeds emerge.
The fastest emergence was at $\theta_g$ of 15 %, followed by $\theta_g$ of 14 and 18 % (Figure 3.6). The 18 % treatment had different emergence results in the two replicate pots sown. Pot 1 had a total of 35 seedlings emerge, whilst pot 2 had only 3, however the $\theta_g$ at sowing of both pots was 17.9 and 17.6 %, respectively. Table 3.4 shows the seed development and Figure 3.6 shows the cumulative emergence curve for the mean of these replicate pots as well as for pot 1 alone.

Table 3.4. The mean gravimetric soil water ($\theta_g$) at sowing and the seed development classified as emerged or germinated in Experiment 2. Each treatment had a total of 110 seeds sown in two replicate pots.

<table>
<thead>
<tr>
<th>Number of replicate pots</th>
<th>Gravimetric water content (%)</th>
<th>Soil water potential (kPa)</th>
<th>Percent of field capacity (%)</th>
<th>Emerged seeds (%)</th>
<th>Germinated seeds (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>14</td>
<td>-102</td>
<td>53</td>
<td>46.8</td>
<td>39.5</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>-62</td>
<td>59</td>
<td>52.7</td>
<td>40.9</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>-32</td>
<td>69</td>
<td>17.3</td>
<td>*</td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>-32</td>
<td>69</td>
<td>31.8</td>
<td>*</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>-18</td>
<td>80</td>
<td>2.3</td>
<td>*</td>
</tr>
</tbody>
</table>

* At 18 and 21 % soil water content, at the end of the experiment soil had dried into hard blocks so recovery of seeds was not possible to check the status of not-emerged seeds.

After 13 days, the pots had dried significantly and the experiment was concluded on day 17, since no additional emergence had occurred. At $\theta_g$ of 18 and 21 %, the soil had dried so that it was difficult to determine the germination status of the seeds that had not emerged. In pot 1 of the 18 % treatment, most seeds germinated but shoot lengths had not reached a length that would allow emergence. At 18 and 21 % $\theta_g$, the seeds which had not germinated became mouldy. In terms of $\psi$, most seeds emerged at -62 kPa, corresponding to 59 % of field capacity. Again treatments with soil at -18 kPa $\psi$, that is approaching soil water contents equivalent to field capacity, showed signs of decreased emergence.
Figure 3.6. Cumulative emergence of chickpea seed at the soil water contents ($\theta_g$) of 14, 15, 18 and 21% in Experiment 2.

Experiments 3 to 5 were conducted to determine the time taken for the chickpea to emerge over a range of $\theta_g$ at sowing and to quantify early differences in root and shoot growth. In the Merredin soil, $\theta_g$ at sowing covered the range 3 to 27%. The lowest treatment had a mean $\theta_g$ of 2.76% ± 0.04, which was the air-dry water content of the soil. Most pots except the air-dry soil experienced some drying of the soil between sowing and harvest (maximum loss equivalent to 7.8% w/w) (Figure 3.7).

Figure 3.7. The relationship between the gravimetric water content ($\theta_g$%,) of each pot at sowing and at harvest in Experiment 3. The 1 to 1 line shows where water content should be if no drying of the soil in each pot had occurred.
Emergence did not start in any treatment until 4 DAS, and no further emergence occurred after 8 DAS (Figure 3.8). At 12 DAS, all remaining pots were harvested. At $\theta_g$ of 3, 8, 10 and 27 %, no chickpea seeds emerged over the duration of the experiment: these corresponded to $\psi$ values dryer than wilting point and wetter than field capacity, respectively. In treatments with 12, 14 and 17 % $\theta_g$ at sowing, all seedlings emerged. The 17 % $\theta_g$ had the fastest rate of emergence, with emergence of all seedlings complete by 5 DAS. Chickpea seeds sown into drier $\theta_g$ had delayed emergence, taking until 4 to 6 DAS at 14 % soil water and 5 to 8 DAS at 12 % soil water. The 23 % $\theta_g$ had one-eighth of seeds emerge on 4 DAS and only one-quarter of seeds had emerged 8 DAS. As with the germination data, as the $\theta_g$ approaches field capacity (-13 kPa), emergence also became delayed, with the fastest rate of emergence at -34 kPa and 100 % emergence reached at $\psi$ as low as -220 kPa.

Where no emergence occurred, germination only occurred in 50 % of the seeds sown into a soil water content of 10 %. All the seeds from the 3, 8 and 10 % $\theta_g$ were viable seed, whilst five-eighths of the seeds from the 23 and 27 % $\theta_g$ became mouldy.

![Figure 3.8. Rate of emergence of chickpea seeds sown into the Merredin sandy clay loam at gravimetric soil water contents ($\theta_g$) ranging from 12 to 23 % in Experiment 3. Note that no seedlings emerged at the $\theta_g$ of 3 to 10 and 27 %. Eight replicates were sown for each treatment.](image)

A preliminary experiment of the emergence of chickpea seeds in HBT soil was conducted in the growth cabinet at Murdoch University (Experiment 4). In the HBT soil, the $\theta_g$ at sowing were from 12 to 23 %. No chickpea plants emerged at the $\theta_g$ of 12 %. The $\theta_g$ of 19 % had the
The fastest rate of emergence, although only 75% of seeds emerged 5 DAS (Figure 3.9). The rates of emergence of chickpea sown at $\theta_g$ of 16 and 22% were similar, with 100% of emergence reached 9 DAS in the 22% $\theta_g$. The drier and wetter treatments of 14 and 23% $\theta_g$, respectively, had delayed emergence and did not reach 100% emergence.

![Graph showing cumulative emergence of chickpea seeds at different $\theta_g$ values.](image)

**Figure 3.9. Rate of emergence of chickpea seeds sown into soil from the High Barind Tract of Bangladesh at gravimetric soil water contents ($\theta_g$) ranging from 14 to 23% (w/w) from Experiment 4.** No chickpea plants emerged at the $\theta_g$ of 12%. Eight replicates were sown for each treatment.

Pot size for the Murdoch University growth cabinet study (Experiment 4) was small and $\theta_g$ declined over the experiment by amounts equivalent to between 0.6 and 2.3% (w/w) across the treatments. To cover a greater range of $\theta_g$ and have pots which allowed greater soil volume for root growth, a second emergence experiment was conducted in Rajshahi, Bangladesh (Experiment 5). This experiment also investigated if priming of the seed for 6 hours influenced emergence of chickpea seed. Soil water contents at sowing ranged from 2 to 27%. In the non-primed seed, no seeds emerged at $\theta_g$ less than 12% or greater than 21% (Figure 3.10). The 16% $\theta_g$ had the greatest rate of emergence at 4 DAS and reached 90% emergence at 6 DAS. Shoots in the 20% $\theta_g$ also started emerging 4 DAS, and 90% emergence was reached 7 DAS. The 12% $\theta_g$ had delayed emergence, 6 DAS, but did reach 100% at 7 DAS. When priming of the seed occurred and the soil $\theta_g$ at sowing was between 16 to 20% chickpea emergence began 4 DAS and at the driest $\theta_g$, of 12% emergence began 5 DAS (Figure 3.10). For all primed seed treatments, emergence only reached 90%. There is no evidence that primed seed had a faster rate of emergence or greater success of emergence in this experiment.
Figure 3.10. Rate of emergence of chickpea seeds sown into High Barind Tract soil of Bangladesh (Experiment 5) at gravimetric water contents ($\theta_g$) ranging from 12 to 27 % with either a) not primed or b) primed seed. No seedlings emerged at $\theta_g$ less than 12 % or greater than 21 % Ten replicates were sown for each treatment.

Of the seeds that did not emerge in all the experiments conducted in HBT soil, those seeds sown at $\theta_g$ of 12 % in the smaller pots had 75 % germination although none emerged by day 10 (possibly due to soil drying out in pot) (Table 3.5). Seeds sown at $\theta_g$ of 2 and 6 % did not germinate regardless of seed priming treatment. At the wetter $\theta_g$ greater than 23 %, if the seeds did not emerge it was because they did not germinate.
Table 3.5. The growth of each chickpea seed as classified at harvest. Seeds were sown in High Barind Tract soil (HBT) of Bangladesh soil at soil water contents between 2 and 27%. Data is presented for experiments conducted in the growth cabinet at Murdoch University, Western Australia (Experiment 4) and a study conducted in Rajshahi, Bangladesh (Experiment 5). Seeds were either classified as emerged, not-emerged but with root and shoot development, not-emerged with root development only or not-germinated.

<table>
<thead>
<tr>
<th>HBT Soil at Murdoch University Growth Cabinet (n =8)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil water content (%)</td>
<td>Emerged (%)</td>
<td>Not-emerged (%)</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>87</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>86</td>
<td>0</td>
</tr>
<tr>
<td>22</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>23</td>
<td>50</td>
<td>0</td>
</tr>
</tbody>
</table>

*only 7 seeds recovered

<table>
<thead>
<tr>
<th>HBT Soil at ambient conditions, Rajshahi, Bangladesh (n =10)</th>
<th>Not Primed seed</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil water content (%)</td>
<td>Emerged (%)</td>
<td>Not-emerged (%)</td>
<td>Root and shoot development only</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>90</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>95</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>27</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

*b n = 20 seeds

<table>
<thead>
<tr>
<th>HBT Soil at ambient conditions, Rajshahi, Bangladesh (n =10)</th>
<th>Primed seed</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil water content (%)</td>
<td>Emerged (%)</td>
<td>Not-emerged (%)</td>
<td>Root and shoot development only</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>90</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>19</td>
<td>90</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>21</td>
<td>90</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>27</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>
Soil water contents from sowing to harvest in the Rajshahi pot trial did not vary much over time within each soil water treatment. The 2 and 6 % treatments increased weight by 0.3 to 0.8 %, other treatments lost up to 0.9 %: the greatest loss of water was treatment 18 %, not primed, which lost 3 % (Figure 3.11). These increases in weight in the dry soil conditions may be attributed to moisture absorption from the atmosphere as conditions were not as controlled as would be available in a growth cabinet.

The highest rate of emergence in the Bangladesh soil was at soil water potentials of -81 to -139 kPa, but emergence was delayed in drying soil to -274 to -538 kPa and in wetter soil at -56 kPa. No emergence occurred at soil water contents which correlated with soil water potentials drier than -538 kPa or wetter than -33 kPa.

![Graph of soil water content](image)

Figure 3.11. Mean soil water content at sowing (n =2) and harvest (n =10) for the chickpea emergence pot trial conducted in Rajshahi, Bangladesh using High Barind Tract soil, Experiment 5. Error bars indicate 1 standard error of the mean where visible.

3.3.3 Emergence of chickpea at different soil bulk densities and aggregate size distribution

Experiment 6 investigated chickpea emergence and shoot characteristics with increasing bulk density. Bulk density was uniform throughout each core at levels between 1.3 and 1.9 g/cm³.

The mean \( \theta_e \) below the seed was 13.3 ± 0.07 % and above the seed was 8.2 ± 0.15 %. There was no difference among treatments in water contents at harvest. Shoot length was limited due to the inability of shoots to penetrate through the compacted upper layer of the pots. No
chickpea shoots emerged in any bulk density treatment. Shoots attempted to grow in the gap between the upper and lower pot, the length being 0.45 to 1.5 cm, with no significant difference among treatments (Figure 3.12).

![Figure 3.12. The shoot length (cm) of chickpea seeds sown in soils compacted to bulk densities between 1.3 and 1.9 g/cm³ in Experiment 6. Error bars indicate 1 standard error of the mean.](image)

Root growth did occur and responded to treatments (Figure 3.13). The mean root length was greatest in the soils at 1.3 g/cm³ bulk density, and decreased by 84 % with increasing bulk density to 1.9 g/cm³. Root length was significantly reduced by increased bulk density ($P < 0.001$) but generally root length was not significantly different between treatments differing in bulk densities by increments of only 0.1 g/cm³ (Figure 3.13). This was observed in the length of both the main roots ($P < 0.001$) and the lateral roots ($P = 0.01$) (Figure 3.14).

Soil penetration resistance increased with bulk density from 0.58 to 1.34 MPa ($P < 0.001$) (Figure 3.15). Pots with low bulk density (1.3 to 1.4 g/cm³) had significantly lower resistance than those with high bulk density (1.8 to 1.9 g/cm³). The relationship of soil penetration resistance below the seed with root length and shoot length was the same as the relationship with bulk density (Figure 3.16). With increasing soil penetration resistance below the seed created by the bulk density treatments, root length and shoot length decreased.
Figure 3.13. The total root length (cm) of chickpea seeds sown in soils compacted to bulk densities between 1.3 and 1.9 g/cm$^3$ in Experiment 6. Mean root lengths with identical letters are not significantly different. Error bars indicate 1 standard error of the mean.

Figure 3.14. The main root (a) and lateral root (b) length (cm) of chickpea seeds sown in soils compacted to bulk densities between 1.3 and 1.9 g/cm$^3$ in Experiment 6. Mean root lengths with identical letters are not significantly different. Error bars indicate 1 standard error of the mean.
Figure 3.15. The mean soil penetration resistance (MPa) of the below-seed layer at sowing of the chickpea seeds into soils compacted to bulk densities between 1.3 and 1.9 g/cm$^3$. Mean penetration resistance bars with identical letters are not significantly different. Error bars indicate 1 standard error of the mean.

Figure 3.16. The relationship between mean soil penetration resistance (MPa) of the below-seed layer at sowing of the chickpea seeds and (a) mean root length or (b) mean shoot length. Soil was compacted to bulk densities between 1.3 and 1.9 g/cm$^3$. Error bars indicate ± 1 standard error of the mean.
Cultivated seed-beds have differentially compacted soil with depth in the seed-bed, therefore the next experiment (Experiment 7) investigated the effect of different aggregate size and uncompacted soil above the seed in combination with two levels of below-seed bulk density. Soil water content was kept constant throughout the core.

At sowing, the $\theta_g$ of the below-seed, and the above-seed <4 mm and >4 mm aggregate sizes were all 13.8 ± 0.68 %, while for the above-seed <2 mm aggregate size $\theta_g$ was 9.97 ± 0.64 % (Table 3.6). This loss of 4 % soil water at sowing may have been due to the preparation of the <2 mm aggregate size soil which allowed evaporation from the soil just prior to sowing. The sampling for $\theta_g$ occurred at potting, therefore it was not possible to compensate for this loss of water due to evaporation.

Table 3.6. Gravimetric soil water contents ($\theta_g$) at sowing for soil in each treatment component of the cores in Experiment 7. Components are the 0-3 cm above-seed soil layer with aggregate sizes of <2 mm, <4 mm or >4 mm and the below-seed soil (3-12 cm depth).

<table>
<thead>
<tr>
<th>Component</th>
<th>Gravimetric soil water content at sowing (%)</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below-seed soil &lt; 4 mm</td>
<td>13.9 ± 0.48</td>
<td>10</td>
</tr>
<tr>
<td>Above-seed &lt; 2 mm</td>
<td>10.0 ± 0.64</td>
<td>3</td>
</tr>
<tr>
<td>Above-seed &lt; 4 mm</td>
<td>13.8 ± 0.68</td>
<td>5</td>
</tr>
<tr>
<td>Above-seed &gt; 4 mm</td>
<td>13.6 ± 0.10</td>
<td>3</td>
</tr>
</tbody>
</table>

Regardless of treatment, at harvest the mean $\theta_g$ of the below-seed soil was between 11.8 and 12.5 %, and the above-seed soil was 5.8 to 8.3 % (Figure 3.17). There were no significant differences in below-seed soil water contents among treatments, however the mean soil water contents of the above-seed soil was less in the <2 mm treatments, and highest in the >4 mm samples.
The ten seeds in each treatment were classified as either emerged or not-emerged. The not-emerged seeds were further classified as having root and shoot development only, root development only or not-germinated. Table 3.7 summarises the germination and emergence characteristics of the seeds in each treatment. The first seedling emerged in T3 (>4 mm, 1.3 g/cm³) with 1 seed on day 7. However, the fastest rate of emergence was T5 (>4 mm, 1.8 g/cm³) followed by T3 (Figure 3.18). These treatments both had the >4 mm aggregate size in the above-seed soil but different below-seed soil bulk densities. No treatment had 100% emergence: the best were T3 and T5 that had 80% emergence whilst T2 (<2 mm, 1.3 g/cm³) and T4 (<2 mm, 1.8 g/cm³), had 60 and 40% emergence, respectively, and T1 (1.3 g/cm³ entire pot) had no emergence. In T2, T3 and T5 there was a peak in emergence during 8 to 10 days; while T4 had a constant emergence of 1 new seed per day (Figure 3.18).

The fastest rate of emergence was in the soils with >4 mm aggregates above the seed regardless of bulk densities below the seed. The increased aggregate size improved germination and emergence. This may have been due to the slight increase in $\theta_g$ of these treatments in comparison to the <2 mm treatment. It could also be due to the way the smaller diameter aggregates packed together, which inhibited emergence of the shoot.
Table 3.7. The growth of chickpea seeds as classified at harvest in Experiment 7. Seeds were classified as either emerged (%), not-emerged but with root and shoot development (%), not-emerged with root development only (%) and not-germinated (%). Each treatment has a total of 10 seeds.

<table>
<thead>
<tr>
<th>Treatments (above-seed aggregates size over below-seed bulk density)</th>
<th>Emerged (%)</th>
<th>Root and shoot development (%)</th>
<th>Root development (%)</th>
<th>Not-germinated (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1, 1.3 g/cm³ entire pot</td>
<td>0</td>
<td>70</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>T2, &lt;2 mm over 1.3 g/cm³</td>
<td>60</td>
<td>30</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>T3, &gt;4 mm over 1.3 g/cm³</td>
<td>80</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>T4, &lt;2 mm over 1.8 g/cm³</td>
<td>40</td>
<td>30</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>T5, &gt;4 mm over 1.8 g/cm³</td>
<td>80</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 3.18. Cumulative emergence of chickpea seedlings sown in Merredin soil in Experiment 7. Treatments were combinations for layers above or below the seed. Bulk densities were either 0.9 (above-seed), 1.3 or 1.8 g/cm³. Soil aggregate sizes were <2 mm, >4 mm or <4 mm. Refer to Table 3.2 for further details.

When emerged seeds were considered only, the main root length was less in the soils compacted to 1.8 g/cm³ bulk density compared with the 1.3 g/cm³ bulk density (P =0.001) (Figure 3.19). In contrast, the lateral roots of the seed in the 1.8 g/cm³ bulk density soils were greater in length than the 1.3 g/cm³ bulk density soils (P <0.001). This confirmed visual observation that the main roots in the 1.8 g/cm³ bulk density soils were short, thick and curled.
and the lateral roots grew across the interface of the base and top core along the path of least resistance. Total root length was not different among treatments. The aggregate size of the surface soil did not affect the root growth of the chickpea seed.

Figure 3.19. Main root, lateral root and total root lengths for the seeds which did emerge in Experiment 7. Error bars indicate 1 standard error of the mean. The numbers of emerged seeds in each treatment are given in Table 3.7.

All the pots where no seedlings emerged were harvested on day 15. In soils compacted to 1.3 g/cm³ throughout the pot, all the seeds germinated and 70 % of them had shoot growth (Table 3.7). Although these pots had no emergence they did have a mean total root length of 24.4 cm which was greater than the mean total root length of the other not-emerged seeds in other treatments (Figure 3.20). Where the soil was compacted above and below the seed to 1.3 g/cm³, shoot growth was restricted but these seeds exhibited the greatest total root growth of all treatments. These seedlings all had some shoot growth, as the seedling attempted to find a pathway to emerge from the soil.

Of the other treatments where seeds did not emerge, with the exception of T5, the root growth was less than that of the emerged seeds of the corresponding treatment. This suggests that root growth was limited in these seeds and this may have been the factor limiting emergence.
Figure 3.20. Main root, lateral root and total root lengths for the seeds which did not emerge in Experiment 7. Error bars indicate 1 standard error of the mean. The numbers of emerged seeds in each treatment are given in Table 3.7.

3.4 Discussion

3.4.1 Effect of soil water content and aeration on germination and emergence of chickpea

3.4.1.1 Soil water and soil aeration

The Merredin and HBT soil types exhibited similar behaviour in the emergence characteristics of chickpea under different soil water contents. The rate of germination and emergence of chickpea seeds was fastest in both soils when initial $\theta_g$ at sowing was between 17 and 18 %. At the drier $\theta_g$ of 10 %, germination did not occur and at 12 %, emergence was delayed. In wet conditions, above 23 % $\theta_g$, germination was limited and delayed and emergence was prevented altogether. By contrast, in the literature, across a range of soil textures, optimum chickpea germination and emergence was reported to occur with $\theta_g$ from 9 to 34 %, while emergence declined with soil drying (Figure 3.21) (Saxena et al. 1983; Sharma 1985; Johansen et al. 1997; Hosseini et al. 2009a).

A closer examination of chickpea emergence results from previous studies can explain the apparent discrepancy with the present results (Figure 3.21). In particular it was noted that: (i) previous studies had not reported an upper limit of $\theta_g$ above which soil water limits emergence, and (ii) that the range of $\theta_g$ over which chickpea reached 80 to 100 % emergence was quite
When the relationship between $\psi$ and emergence was compared for the available data (Figure 3.21b) for the three soils (Merredin soil, Bangladesh soil, silty clay textured soil reported by Sharma (1985)), $\psi$ was comparable where the emergence was highest (80 to 100 %), even though the associated $\theta_g$ were quite different (Figure 3.21a). The studies where $\theta_{fc}$ were lower (25 and 19 %), have a lower range in $\theta_g$ over which optimum emergence occurred (present study and Hosseini et al. 2009b). Where $\theta_{fc}$ was higher, such as in Sharma (1985) and Saxena et al. (1983) who reported $\theta_{fc}$ was 34 and 32 %, respectively, optimum emergence occurs at a higher range of $\theta_g$.

Figure 3.21. The percentage emergence of chickpea seedlings with different soil water content and soil water potential across different studies in Western Australia (present study and Hosseini et al. (2009b)), Bangladesh (present study) and India (Saxena et al. 1983; Sharma 1985).
The water release curves of the Merredin and Bangladesh soils are different (Figure 3.2) with the $\theta_{fc}$ at -10 kPa being higher in the silt loam soil of Bangladesh by approximately 10 %. In comparison at the dry end of the water release curve, the $\theta_{wp}$ (-1500 kPa) is only 2 % higher. This means that at optimum rates of chickpea germination and emergence, each soil type had slightly different $\psi$. In wet soil, chickpea seeds sown in the Merredin soil type showed optimum germination at -13 kPa and emergence at -34 kPa, whereas in HBT soil optimum emergence was at -62 kPa. Germination was recorded at -162 kPa, but since dryer soils were not tested we have not reached the critical minimum soil water potential for germination reported to be -600 kPa (Hadas and Russo 1974). In both soil types, as the soil dried and the $\psi$ decreased, emergence became delayed but was still possible up to -220 kPa in Merredin soils and -583 kPa in Bangladesh soils. Hence the present results indicate that the $\psi$ at which emergence was not possible was close to wilting point in dry soils and close to field capacity in wet soils, indicating too much and too little water can both limit emergence.

Few researchers have reported limits for germination in both dry and wet soils. Dasberg and Mendel (1971) reported that germination of ricegrass (*Oryzopsis holciformis* (M.B.) Richt.) was only 50 % of maximum at -10 kPa (wet end) and -500 kPa (dry end). Emergence was possible at lower $\psi$ (drier limit) in Bangladesh soil than in Merredin soil, whilst chickpea in the Merredin soil was able to emerge at higher $\psi$ (wetter limit) (Figure 3.21). The differences in $\psi$ at which emergence becomes limiting may be due to the finer texture class of the Bangladesh soil compared to the Merredin soil (Collis-George and Sands 1959; Dasberg and Mendel 1971). These differences in particle size will affect pore size distribution and soil aggregate structure. Soils with finer texture classes enabled seed to germinate at lower minimum $\psi$ than in coarse textured soils, but coarser textured soils enable germination at higher maximum $\psi$ (Collis-George and Sands 1959; Dasberg and Mendel 1971). The Merredin soil with 61 % sand and 29 % clay had 17.7 % $\theta_g$ at -33 kPa, the Bangladesh soil with 42 % sand and 28 % clay had 27 % $\theta_g$ at -33 kPa whilst a clay soil (Sharma (1985)) with 12 % sand and 58 % clay had 34 % $\theta_g$ at -33 kPa. The soil with the higher clay content will potentially have more micropores, whilst the soils dominated by sand are expected to have more mesopores and macropores. The clay textured soils will also potentially have a greater proportion of smaller aggregates and more of
the finer pores which permit greater seed-soil contact and movement of water to the seed (Brown et al. 1996; Atkinson et al. 2007). The higher clay content soil although having greater soil water content at the same soil water potential, does not necessarily have all that water available for plant uptake. As pointed out in Collis-George and Sands (1959) both the soil water content and soil water potential should be determined in germination studies. Indeed the present results indicate that soil water potential is the preferred variable to use to compare among studies and hence to describe soil water treatments designed to screen germination and emergence characteristics of seeds.

Sufficient oxygen supply is required for germination and emergence to support metabolic activity and seed respiration (Hadas 2004). However, when soil water content is too high or soil is too compact, diffusion of oxygen to the seed may be impaired (Dasberg and Mendel 1971; Singh and Ghildyal 1977; Kirkegaard et al. 1992). Ten percent air-filled porosity was estimated at θ_{afp} of 25 to 20 %, in the Merredin soil and 30 to 25 % in the Bangladesh soil. Failure to emerge in the both soils and failure to germinate in the Merredin soil occurred at θ_{g} of 27 %, which was at less than 10 % air-filled porosity in Merredin soil but in the Bangladesh soil was within the 15 % air-filled porosity limit. At these soil water contents, ψ was -6 and -33 kPa in the Merredin and Bangladesh soils, respectively, which were in the range of those ψ reported as limiting oxygen availability in other studies, or having limited root elongation (Kirkegaard et al. 1992). The HBT soil has very low soil organic matter levels (Brammer, 1996) and is subject to annual wet puddling for rice transplanting. Hence it is likely that limited aggregation occurs in this soil and that the relative abundance of mesopores and macropores in this soil is lower than would be expected in a soil with 28 % clay.

Seed germination and emergence are delayed until the chickpea seed requirements for water and oxygen are met. In the instances of dry soil (θ_{g}, 12 %), the germination and emergence delay may be attributed to the increased time required for the seed to imbibe water to start the process of germination. While emergence was delayed by low soil water, it still reached 90 and 100 %, a similar success rate to the moderately wet soils (θ_{g}, 14 to 21 %) (Figures 3.6, 3.8 and 3.9). Collis-George and Sands (1959) commented that the hydraulic conductivity of the soil
was also important, that a drier soil was less able to transmit water, and had a reduced rate at which water can reach a seed than in a wetter soil, resulting in decreased germination rate.

When the soil was initially very wet ($\theta_g \geq 23\%$), germination was delayed and indeed the onset of germination coincided with a partial drying of the soil (Figure 3.2). However, in the greater volume of soil used in the emergence trial (Figure 3.8), the wet soil treatments ($\theta_g$ at 23 and 27 %) did not experience drying of the soil and most (75 and 100 %) of the seeds did not germinate and were no longer viable after retrieval. Hence the commencement of germination may have been delayed until both the water and aeration requirements of the germinating seed were met. If a soil is wet at sowing and remains near or above field capacity ($\theta_g \geq 23\%$), the present results suggests that few chickpea seeds will germinate and emerge on silty clay soils similar to those studied here. If rapid drying occurs soon after seed placement, some seed germination and emergence may be recorded. A clear implication of the present results is the need to avoid sowing chickpea into wet soils. This will be examined further in Chapter 4.

3.4.1.2 Shoot development

In addition to germination assessment, the development of shoots was also made in the present germination experiments. This allowed a comparison of the start of shoot development with that of roots, which was not possible in the emergence experiments where shoots had to penetrate 3 cm of soil before emerging. Shoot development at germination mirrored that of emergence with regard to soil water content, where emergence of chickpea was successful at $\theta_g$ from the 18 to 23 %. When the $\theta_g$ was outside of this range, shoot development was evident in only 21 % of the seeds in the wet soil (-6 kPa $\psi$) and 33 % of the seeds in the dry soil (-99 kPa $\psi$). It has been noted in other research in species which exhibit both epigeal and hypogeal emergence that seedling growth and emergence tolerates a narrower range of $\psi$ than germination (Dasberg 1971; Dasberg and Mendel 1971; Fyfield and Gregory 1989; Dracup et al. 1993). In the present study this was consistent with the limited shoot development of chickpea seedlings at the very wet and dry soil water contents. Soil water potential has been recorded to be limiting in lupin for growth at -1000 to -2000 kPa but emergence was more sensitive than germination (Dracup et al. 1993). In mungbeans, 50 % germination was reported
at $\psi$ of -1700 kPa, but emergence was limited to 50% at $\psi$ dryer than -500 kPa (Fyfield and Gregory 1989), and Dasberg (1971) noted that seedling roots of ricegrass seemed to be less affected by low soil water content than shoots.

3.4.1.3 Seed priming

In the present study priming of the seed was not found to improve chickpea seed emergence at dry $\theta_g$, nor improve the rate or final percent of emerged seedlings at any $\theta_g$. The duration of soaking of the seed and subsequent drying were within the range recommended in previous studies on chickpea seed priming (Musa et al. 2001; Harris et al. 2005). However quantification of the amount of water imbibed by the primed seed was not carried out. It should be noted that the seeds were well covered by soil in the pots and that the seed-soil contact would have been good as soil aggregates were < 4 mm in diameter. While there are many field studies on the benefits of seed priming, studies in pot trials of cotton ($Gossypium hirsutum$ L.) and maize showed no improvement in emergence and seedling growth with priming after 8 days (Murungu et al. 2003). In the current pot trial if seedlings were permitted to grow for a longer period of time, rather than be harvested at emergence differences in early growth vigour may have become evident.

Seed priming was developed for broadcast systems of sowing where seeds are sown into a drying surface soil. The seed-bed in these systems produces variation in surface soil covering of the seed, seeding depth, aggregate size and soil water content. In such tillage systems, priming provided an advantage for emergence and early growth of chickpea, maize, and cotton (Musa et al. 2001; Murungu et al. 2003). Field studies in the HBT indicate that the $\theta_g$ at sowing was between 15.2% and 23.9% in 2007-2009 (Chapters 4 and 5): this indicates that $\theta_g$ were not as low as applied in the present pot study. Soil water contents at 12% showed no advantage to seed priming in this pot experiment, whilst the next driest $\theta_g$ was 6%, at which water content no emergence occurred in the primed or not primed seed. This suggests that soil water contents at sowing in the field in the HBT in 2007-2009, did not reach levels which prevent emergence and that in such conditions when the seed-bed was prepared to have well-covered seed and of adequate aggregate size distribution, priming of the seed would not be required. However, in
the context of the development of minimum tillage in the HBT for chickpea and other crops, it is expected that seeds will be placed in limiting environments in regards to seed-soil contact and soil covering the seed, therefore seed priming, would still be an advantage in this environment. However, when mechanised sowing and minimum tillage speed up the process of sowing and shorten the time taken from harvest of the rice crop to sowing of the chickpea crop, water loss of the sown seed-bed should also be minimized. Hence, priming of the seed may become less necessary for reliable seedling establishment in minimum tillage systems. However, the low risk, low cost and minimal labor required for seed priming (Harris et al. 2005) also means that there would be no negatives to continued use of seed priming unless the seed-bed soil was very wet. However, the susceptibility of the primed seed to damage in the seed meter and after seed placement by mechanised sowing also needs to be assessed.

3.4.2 Effects of soil bulk density and aggregate size on emergence of chickpea

Soil water holding capacity is driven by factors such as soil bulk density and aggregate size and these factors can determine the development of plant roots and shoots. High soil bulk density and increased soil strength can delay or limit germination and emergence and restrict the development of shoots (Nasr and Selles 1995). Root elongation rate and root length both decrease with increased soil strength (Materechera et al. 1991). Aggregate size can affect the contact of the seed with the soil, and therefore determine water uptake of the seed and its germination. In addition aggregate size can affect the packing of the soil, the size, shape and numbers of voids and cracks which also affects the growth of roots and shoots (Nasr and Selles 1995). The development of the shoot may be affected differently to the roots under adverse soil physical conditions, so therefore in a seed-bed, the soil physical conditions below and above the seed are both important.

In this work the prime interest was in the early growth of the chickpea seedlings, and most importantly whether roots were able to penetrate the drying surface and distribute into the wet soil below. This would allow rapid initial growth of chickpea which can result in increased seed yield (Johansen et al. 1997). The experiments where the seed was sown into a prepared soil and covered loosely (essentially a dibbling technique), showed delayed emergence at low water
contents (Experiments 2 to 5), whilst in the experiments where the seed was placed under a compacted layer of soil (packed to bulk densities of 1.3 g/cm$^3$ and greater above the seed, at $\psi$ of -182 kPa), there was no emergence (Experiments 6 and 7). Seedling emergence can be limited when blocked under clods or crusting (Dorsainvil et al. 2005), and in this case shoots had a tendency to grow into the gap created by the two soil layers, therefore the shoots developed and elongated through the gap, regardless of the soil bulk density or soil strength above it. However, the shoots were unable to penetrate through the surface of the core indicating that in a seed-bed with uniform compaction above the seed, emergence may be limited, even though shoots have the ability to develop in gaps and to push apart what essentially in this experiment became a large clod face. In a seed-bed prepared via strip tillage, zero tillage or SPST, seedlings are unlikely to be confined below a large clod of high strength (Chapter 5). In the broadcast seeding system, there will likely be a distribution of aggregates from small to large plus clods in the seed-bed layer. Hence seedling emergence of chickpea was likely to be limited, but not prevented by the presence of larger clods. In this present study, there is evidence that chickpea seedlings have the ability to emerge around large clods above a seed by making use of gaps between the clods and aggregates. Chickpea seedlings respond to impeding conditions by swelling and increasing their epigeal diameter allowing them to exert more force to push through surface crusts (Sivaprasad and Sundara Sarma 1987). The delay to seedling emergence in compacted soil, where the volume of voids in the soils was reduced, can be due to the increase in the length of the pathway the seedling shoot must take to reach the soil surface (Nasr and Selles 1995). Seedling growth after emergence has been reported to be affected by increased soil strength due to indirect responses such as inhibition of root growth (wheat) (Masle and Passioura 1987), however other research with pigeonpea (Cajanus cajan L.) suggested that where water and nutrients were not limiting and where there was unlimited root growth in some layers of the soil, shoot growth may not be limited by soil strength (Kirkegaard et al. 1992). In field conditions, the ability of lateral roots to penetrate into uncompacted layers of soil can provide adequate supply of water and nutrients to the plant in conditions where growth of the main roots is impeded by a hardpan.
Chickpea seeds were able to emerge (40 to 80 % success) from soil where the seed was covered by loosely packed aggregated soil, regardless of the soil compaction below the seed. In this present study, the soil which had the greater aggregate size of >4 mm had the fastest rate of emergence regardless of below-seed soil bulk density. By contrast, in previous studies, finer aggregates were generally associated with improved rate and final emergence due to better seed-soil contact, and water uptake to the germinating seed (cotton, and maize, study was for above-seed conditions; wheat study was for above and below-seed conditions) (Nasr and Selles 1995; Murungu et al. 2003). However, soil bulk density of >1.2 g/cm³ and penetrometer resistance of >1.4 MPa delay seedling emergence (wheat) (Nasr and Selles 1995). These levels are above the levels of bulk density (1 g/cm³) and penetrometer resistance (below 0.2 MPa) above the seed in the present study, for both aggregate sizes. The contrasting effects of aggregate size on emergence to that of previous research (Nasr and Selles 1995; Murungu et al. 2003) was attributed to the soil water content of the above-seed soil rather than the soil physical factors of aggregates size, or soil strength. Aggregate size distribution has been found to have less influence on seedling emergence than $\Psi$ (Cook et al. 1995). In the present study, the water content of the <2 mm layer was 4 % lower than the >4 mm aggregate layer which may also have delayed germination. The $\theta_g$ was 10 % above the seed in the <2 mm aggregate size layer which was less than the minimum required for successful emergence reported earlier ($\theta_g$ of 12 %). In this case the movement of water from the soil to the seed would limit water uptake (Dasberg 1971), however, the $\theta_g$ below-seed was 14 %, which should compensate for the lack of water contributed by the above-seed soil to the seed, and still allow germination and emergence to occur, albeit with a delay.

Soil strength as measured by penetrometer resistance was also discounted as a limiting factor to shoot emergence in this experiment. Soil strength at such low values has a negligible effect on plant root growth (Iijima and Kato 2007) and given the ability of the shoots to move the compacted (3 cm layer) above the seed in the Experiment 6 (this chapter), the elongation of chickpea seedlings was unlikely to be limited by these small aggregates. Penetrometer resistance of loosely packed, low bulk density soil will be low regardless of the aggregate size: only at higher bulk densities will penetrometer resistance register differences (Nasr and Selles
1995). In addition, Kirkegaard et al. (1992) found no direct effect of soil strength on shoot height when the germinated seeds of wheat were sown above a compacted layer and soil was pressed over the seeds, and in Experiments 3 to 5 (this chapter) when the seed was dibbled into the soil, chickpea shoots were uninhibited.

While shoots were relatively unresponsive to increasing bulk density, the roots on the other hand were significantly impeded as bulk density increased. The elongation rate of radicles of many species have been shown to follow an inverse response to increasing soil strength with 2 to 3.7 MPa being the critical threshold of soil strength at which radicle elongation for a variety of species was prevented (Kirkegaard et al. 1992; Hodge et al. 2009). Kirkegaard et al. (1992) also found that the elongation of the radicles of pigeonpea were more sensitive to high soil strengths than the seedling roots. The roots respond to increasing soil strength by increasing the root diameter behind the root tip and decreasing root elongation (Hodge et al. 2009). The root length of chickpea was depressed at soil strengths of 1.3 MPa, but soil strength did not totally inhibit growth of the roots, and main root and lateral roots were equally affected (Figure 3.16).

Main root length of 12 cm or more indicated unlimited root growth under soil strengths of 1 MPa as this was where the roots reached the base on the pot. At soil strengths greater than 1 MPa root lengths were less than 50 % of the maximum. As strength of a compacted layer increases the proportion of roots that penetrate it will decrease (Dexter 1986). Plant roots under impedance exert a growth pressure ($\sigma$) which enables them to elongate through voids in the soil which are smaller than the root diameter, by displacing soil and overcoming friction (Clark et al. 1996). At maximum root growth pressure ($\sigma_{\text{max}}$), root elongation is no longer possible, and has been reported to vary with species but also with the measurement method (Clark et al. 2003a). High maximum axial pressure does not necessarily mean plant roots can penetrate strong soil (Hodge et al. 2009), but it is interesting to note that $\sigma_{\text{max}}$ of lateral roots of pea were found to have a similar $\sigma_{\text{max}}$ to main roots (Misra 1997), which may be an indication as to why in the uniformly compacted soil main roots and lateral roots of chickpea reacted in a similar manner to increased compaction. Lateral roots are finer than main roots and as such should be able to penetrate smaller pores (Clark et al. 2003a). However, compaction apparently increased the proportion of small pores and hence would also have decreased both lateral and main root.
elongation. Root elongation could also be affected by oxygen availability, as in the soil which had been compressed to a higher degree there was more water contained within the soil matrix (Kirkegaard et al. 1992; Iijima and Kato 2007). At the high bulk density of 1.8 and 1.9 g/cm$^3$, the air-filled porosity was less than 7.5 % which can limit oxygen supply and limit root growth (Dexter 1988). High bulk density limited development of chickpea seedling roots due to limiting soil strength and aeration, even at soil water contents which were dryer than optimum in the previous germination and emergence experiments.

In soil under uniform compaction (1.3 to 1.9 g/cm$^3$) above and below the seed, emergence did not occur, and main root and lateral root growth both decreased to the same degree with increased bulk density (Figure 3.14). In the experiment where above-seed soil was loosely packed, total root growth was not different in the emerged seedlings when the soil below the seed was compacted to 1.3 or 1.8 g/cm$^3$ (Figure 3.19). However, at the two bulk densities the seedlings exhibited different root growth characteristics. At the low bulk density (1.3 g/cm$^3$), the main root of seedlings grew unimpeded to the base of the pot, and produced minimal lateral roots. In the highly compacted below-seed soil (1.8 g/cm$^3$), the seedling was unable to send the main root directly through the soil and in response produced lateral roots, which grew in the gap between the surface and base layers of the pots, the path of least resistance. When main roots are slowed in growth due to a compacted layer, proliferation of lateral roots in the unconfined layer above can occur (Kirkegaard et al. 1992). This type of response is common among plant species and can also occur due to low water content, high soil strength and where larger aggregates dominate (Dexter 1986). For chickpea which encountered soil compaction in this experiment, the total root length was 9.7 cm (T4) to 12 cm (T5) with 76 and 64 % of that root length, respectively, being contributed by the lateral roots. With uniform bulk density of 1.8 g/cm$^3$ throughout the core, total root length was 5.9 cm, 47 % of which was contributed by lateral roots. In fact, in all the uniformly compacted pots after 8 days, lateral root length made up 47 ± 2 % of the total root length (Figure 3.14). It has been found that roots were able to elongate into cracks of equal or greater width than the root tip diameter (Dexter 1986). In the pots with loose surface soil, the lateral roots that developed and accessed the interface between
the hard layer and the loose surface would have had very little resistance to elongation, and would have not needed to generate much force to grow between the aggregates.

In seed-beds where hard layers are produced under the surface soil layer, the effect of an increase in bulk density may result in root growth being confined to the surface soil. Such hard layers may develop with drying of the surface soil, when there are large aggregates in the seed-bed or if there are soil textural changes in the profile (Dexter 1986). In the HBT, hard layers may develop due to the cultivation techniques and puddling of the soil for rice production in the kharif season (Johansen et al. 2008b). These hard pans are often found at a depth of 10-15 cm. The early root growth of the confined root system may then be concentrated in the shallow surface layer which is quickly drying, which may compromise early plant growth. The role of mechanised tillage in alleviating or exacerbating the strength of a hard pan may therefore be critical in determining the success of crop establishment.

3.5 Conclusion

The rate of germination and emergence of chickpea seeds was fastest in silty clay soils which had $\theta_g$ at sowing between 17 and 18 % (w/w). As the soil dried to 12 %, emergence may be delayed and below 10 %, germination did not occur. In wet conditions above 23 % soil water, germination and emergence were both limited and delayed. In addition, emergence of the epicotyl of the chickpea seed was more limited in dry soil conditions than root growth. In both soils, emergence was only recorded within the limits of field capacity (-10 kPa) and wilting point (-1500 kPa). Emergence was possible at lower $\psi$ in the finer textured Bangladesh soil, and at higher $\psi$ in the slightly coarser textured Merredin soil type. The range in optimum $\psi$ of each soil type for chickpea emergence may reflect the different soil particle and pore size distributions which in turn can affect seed-soil contact and hydraulic conductivity. These characteristics will affect the movement of water to the seed and the aeration requirement of the seed for germination.

In wet conditions, germination and emergence can be limited due to insufficient oxygen supply, with 10 % air-filled porosity being the limit recommended in literature. The air-filled porosity where emergence was limited at the wet end of soil water content was <10 % in the
Merredin soil and at 15% in the Bangladesh soil, corresponding to soil water potentials of -6 kPa and -33 kPa respectively.

Shoots of developing chickpea seedlings were able to tolerate higher bulk density and soil strength than the emerging radicle. Within the root system of the chickpea seedlings, impeded downward growth of the main root due to high bulk density soil was compensated for by increased length of lateral roots. In both Experiments 6 and 7, where high bulk density decreased main root growth a greater proportion of root growth was associated with the lateral roots. This was more pronounced when there were pockets of high porosity, low strength soil they could colonise. In the present study these areas were often found at the interface between core layers where the seed was placed and subsequent shoot development occurred. The shoot forced the core layers apart which allowed preferential growth of the lateral roots. Conclusions about the effect of fine soil aggregate sizes (<2 mm compared to <4 mm) above the sown seed on shoots of developing chickpea seedlings were confounded by the differences in soil water contents of the two treatments. In this work the limiting soil water content in the <2 mm aggregate size treatment delayed emergence. By contrast the bulk density and soil strength of these above-seed layers were not limiting to seedling emergence for both aggregate sizes.

This work suggests that the above-seed and below-seed soil physical properties will impact on the early growth of the chickpea seedling and that at adequate levels of soil water content the soil physical factors of soil bulk density and soil strength can still limit chickpea emergence. The present work suggests that the soil above the seed needs to be loosely compacted (<1.3 g/cm³ bulk density), but the size of the soil aggregates which provides the best germination and emergence is inconclusive. Large clods and high bulk density layers above the seed will limit seedling emergence, whilst high bulk density below the seed will limit seedling root elongation.

Under traditional broadcast-sowing techniques used in the HBT of Bangladesh (described in Chapter 1), the soil water contents at sowing quickly dry beyond the limits to support chickpea crop establishment. In addition, there is a large range in aggregate sizes created in the seed-bed, in the size range from large clods to micro-aggregates. Within the mechanised row-sowing techniques which are being developed for the HBT, the time between rice harvest and sowing of
the chickpea crop is decreased and the larger clods and aggregates are also less likely to occur. With timely sowing the soil water content in the seed-bed is likely to remain within the critical range of $\psi$ (-538 to -33 kPa) which will not prevent seedling emergence. Thereby the problem of rapidly drying surface soil under traditional broadcast-sowing is likely to be overcome. Under the different tillage techniques of zero, strip and SPST (described in Chapter 1) the seed-bed created will have different characteristics in regards to aggregates size, furrow conditions and soil covering the seed. These will affect seed-soil contact, seed water uptake and soil penetration resistance. The following Chapters 4 and 5 study the soil physical conditions at chickpea sowing in Bangladesh to identify when soil conditions in the field under the different mechanised sowing techniques may be limiting chickpea establishment based on the ranges deemed non-limiting in this chapter.
4 The effect of sowing time on chickpea crop establishment and subsequent crop growth in the High Barind Tract of Bangladesh

4.1 Introduction

In Chapter 3, the conditions were described under which chickpea germination and emergence will be limited by soil physical constraints at sowing. In field conditions, the success of chickpea crops grown in the rabi season in the High Barind Tract (HBT) of Bangladesh can be constrained by two factors, both affect conditions at sowing. Firstly, drying surface soil which can limit crop establishment and secondly delayed sowing or emergence which can expose the crop to less than ideal conditions during subsequent crop growth stages. The traditional method of broadcast-sowing of rabi season crops, followed either by incorporation with bullock-drawn country plough or two-wheel tractor (2WT) with rotary cultivator can exacerbate these problems due to the multiple cultivations. This enhances drying of the tilled surface soil and lengthens the time required for sowing, which can lead to sowing of the crop outside of the optimal sowing window.

After the harvest of the rice crop, the surface soil in the HBT can dry quickly and become hardsetting due to high temperatures and high evaporation rates (Musa et al. 2001). Hence, soil water content in the seed-bed is often less than optimal for chickpea establishment by traditional seeding and tillage methods. With rapid germination and emergence, seedling roots are able to penetrate into the soil subsurface quickly with a greater likelihood of achieving adequate plant stands and good grain yields (Fyfield and Gregory 1989; Harris et al. 1999; Gan et al. 2002). Rapid and healthy crop establishment leads to strong root development which minimizes effects of future drought stress. Additional limitations of the broadcast method of sowing are the irregular aggregate size of the seed-bed, poor seed and fertiliser placement in the seed-bed, poor soil coverage of the seed, uneven depth of seed placement and poor seed-soil contact.

Delayed sowing can negatively affect the chickpea crop in relation to crop water requirements and temperatures within the growing season. It can cause the seedlings to emerge under cold temperatures, slowing the rate of early growth (Chaturvedi and Ali 2004; Johansen et al. 2008b). In addition, because of very little in-season rainfall, the crop relies on residual soil
water in the profile for growth, which can be severely depleted towards crop maturity when ambient temperatures also increase (Rahman *et al.* 2000; Johansen *et al.* 2008b). Any delay to crop establishment postpones both flowering and podding and may lead to chickpea pod-filling and seed development occurring under high temperatures and a drying soil water profile, resulting in terminal drought stress and reduced yield (Wang *et al.* 2006; Gaur *et al.* 2008).

The recommended sowing time for chickpea in the HBT, using broadcast seeding and a fully tilled seedbed, is from October to the first week of November (BARI 2010). The actual optimum sowing time depends on when the rice crop is harvested and on when the soil water is optimal for tillage and sowing. However, Johansen *et al.* (2008b) recommended that sowing of chickpea occur between late November and early December, largely to limit the prevalence of Botrytis Grey Mould (BGM) which is the major chickpea disease in Bangladesh.

The development of mechanised row-sowing, independent of the level of soil disturbance (from full tillage through to zero tillage), allows sowing of the chickpea crop in a single pass and expands the area of land that can be planted within the sowing window. It is hypothesised that mechanised row-sowing will facilitate timely sowing within the sowing window and ensure optimum chickpea establishment while minimizing exposure of the chickpea crop to high temperatures and terminal drought later in the growing season.

The optimum sowing time for chickpea in the HBT of Bangladesh needs to be determined for these new mechanised row-sowing techniques. The objectives of the study were to:

1. quantify the soil water and soil strength in the seed-bed at sowing and determine when conditions limit chickpea establishment for mechanised row-sowing; and
2. identify the window for optimum sowing in the HBT to achieve non-limiting soil physical properties at sowing by mechanised row-sowing and limit exposure of the chickpea crop to terminal drought and heat stress.
4.2 Materials and Methods

Three field trials were completed in the HBT of Bangladesh to determine the optimum range of soil strength and soil volumetric water content ($\theta_v$) within which chickpea seeds will germinate and emerge in the field environment. The trials were established in three growing seasons (2007-08, 2008-09, 2009-10) with sowing dates spread from 22 November to 22 December. Hereafter, each trial will be referred to by the year of establishment. Table 4.1 outlines the details of these trials.

The spread in sowing dates across the chickpea sowing period allowed the effect of $\theta_v$ on chickpea seed germination and emergence to be studied. The Chinese made 2BG-6A planter was modified for the different tillage types and was attached to a 2WT (Dongfeng or Sifeng). For the 2007 trial, three tillage types were included as treatments: zero tillage (ZT), strip tillage (ST), and power tiller operated seeder (PTOS). For the PTOS in 2007, a 2WT with full rotary tillage was used to cultivate the soil followed by hand broadcast of seed and fertiliser, followed by another pass with the 2WT to incorporate the seed and fertiliser into the seed-bed. In 2008 and 2009 only ST was used, this comprised of a 2WT with a modified planter attached. Four rotary cutting blades were arranged in front of each furrow opener, which had been modified to deliver both the seed and fertiliser behind the rotary blades and was followed by a pressing roller. The furrow opening was made by a narrow leading edge tine. All discussion relating to tillage type and grain yield for the 2007 trial will be presented in Chapter 5.

Daily temperature and rainfall data were collected by staff from the BRRI (Bangladesh Rice Research Institute) at Edulpur Village, Godagari Upazilla, Rajshahi Division. The weather station was approximately 10 km from the trial sites.
Table 4.1. Details of location, soil type, experimental treatments, plot design and seed and fertiliser rates for sowing date trials established in 2007, 2008 and 2009 in the High Barind Tract of Bangladesh.

<table>
<thead>
<tr>
<th>Growing season</th>
<th>2007-08</th>
<th>2008-09</th>
<th>2009-10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location</strong></td>
<td>Choyghati Village</td>
<td>Nagirpur Village</td>
<td>Choyghati Village</td>
</tr>
<tr>
<td></td>
<td>Godagari Upazilla</td>
<td>Godagari Upazilla</td>
<td>Godagari Upazilla</td>
</tr>
<tr>
<td></td>
<td>Rajshahi Division</td>
<td>Rajshahi Division</td>
<td>Rajshahi Division</td>
</tr>
<tr>
<td><strong>Soil type</strong></td>
<td>Silt loam surface soil (McDonald <em>et al.</em> 1998); General soil type, Grey terrace soil; USDA Soil Taxonomy, Aeric Haplaquept (Catling 1992; Brammer 1996); FAO-UNESCO soil Eutric Gleysol (Catling 1992)</td>
<td>Silt loam surface soil (McDonald <em>et al.</em> 1998); General soil type, Grey terrace soil; USDA Soil Taxonomy, Aeric Haplaquept (Catling 1992; Brammer 1996); FAO-UNESCO soil Eutric Gleysol (Catling 1992)</td>
<td>Silt loam surface soil (McDonald <em>et al.</em> 1998); General soil type, Grey terrace soil; USDA Soil Taxonomy, Aeric Haplaquept (Catling 1992; Brammer 1996); FAO-UNESCO soil Eutric Gleysol (Catling 1992)</td>
</tr>
<tr>
<td><strong>Sowing dates</strong></td>
<td>4 sowing dates: 1, 4, 11, 14 December</td>
<td>8 sowing dates: 22, 24, 26, 28, 30 November and 2, 4, 6 December</td>
<td>4 sowing dates: 3, 6, 14, 22 December</td>
</tr>
<tr>
<td><strong>Tillage types</strong></td>
<td>Power tiller operated seeder (PTOS), Strip (ST) and Zero (ZT)</td>
<td>ST</td>
<td>ST</td>
</tr>
<tr>
<td><strong>Design</strong></td>
<td>Split plot Main plot – sowing date Sub plot – tillage type</td>
<td>Complete randomised block</td>
<td>Complete randomised block</td>
</tr>
<tr>
<td><strong>Replication</strong></td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>Row spacing</strong></td>
<td>50 cm</td>
<td>40 cm</td>
<td>30 cm</td>
</tr>
<tr>
<td><strong>Plot dimensions</strong></td>
<td>6 rows 10 m long</td>
<td>8 rows 10 m long</td>
<td>12 rows 12.8 m long</td>
</tr>
<tr>
<td><strong>Chickpea cultivar</strong></td>
<td>Bari Chola 5</td>
<td>Bari Chola 5</td>
<td>Bari Chola 5</td>
</tr>
<tr>
<td><strong>Seed rate</strong></td>
<td>38 kg/ha</td>
<td>40 to 45 kg/ha</td>
<td>45 kg/ha</td>
</tr>
<tr>
<td><strong>Seed treatment</strong></td>
<td>Primed with water 4 hours, drained and surface dried before sowing</td>
<td>Primed with water 4 hours, drained and surface dried before sowing</td>
<td>Primed with water 4 hours, drained and surface dried before sowing</td>
</tr>
<tr>
<td><strong>Fertiliser rate</strong></td>
<td>Triple superphosphate (TSP) 50 kg/ha</td>
<td>Triple superphosphate (TSP) 100 kg/ha</td>
<td>Triple superphosphate (TSP) 100 kg/ha</td>
</tr>
<tr>
<td><strong>Herbicide</strong></td>
<td>30 November Roundup®&lt;sup&gt;1&lt;/sup&gt; 250 ml / 15 L H2O</td>
<td>21 November Roundup®&lt;sup&gt;6&lt;/sup&gt; 250 ml / 15 L H2O</td>
<td>2 December Roundup®&lt;sup&gt;6&lt;/sup&gt; 250 ml / 15 L H2O</td>
</tr>
<tr>
<td><strong>Hand weeding</strong></td>
<td>None</td>
<td>12 to 15 January 2009 10 to 13 February 2009</td>
<td>None</td>
</tr>
<tr>
<td><strong>Insecticide</strong></td>
<td>Pod-borer Ripcord®&lt;sup&gt;2&lt;/sup&gt; 562 ml/ha at podding stage</td>
<td>Pod-borer Ripcord®&lt;sup&gt;6&lt;/sup&gt; 562 ml/ha 12, 23 February and 2 March 2009</td>
<td>Pod-Borer Ripcord®&lt;sup&gt;2&lt;/sup&gt; 562 ml/ha at podding stage</td>
</tr>
</tbody>
</table>

<sup>1</sup>Roundup® active ingredient (Glyphosate 360 g/L)
<sup>2</sup>Ripcord® active ingredient (21.1 % Cypermethrin, 70.5 % Xylene)
4.2.1 Soil water content and soil strength

Soil water content and soil strength (soil penetration resistance) were monitored from before sowing to after emergence of the crop. Volumetric soil water content ($\theta_v$) was measured by the MP406 soil water probe ($\theta_{probe}$) (ICT international, Australia). The MP406 measures the soil dielectric constant, this technology is known as frequency domain reflectometry. The dielectric constant is shown in millivolts (mV), and converted to $\theta_v$ using an in-built calibration. During all experimental seasons, gravimetric soil water contents were also collected and converted to $\theta_v$ using bulk density (Cresswell and Hamilton 2002). Intact soil cores were extracted from soil pits in the 2008 tillage type experiment (Chapter 5). The core dimensions were 2.7 cm high and 4.65 cm diameter. Two replicate cores were removed at each of the depths of 5, 10, 15, 20, 30 and 40 cm. After oven dry (105 °C) weights were determined, bulk density was calculated (Cresswell and Hamilton 2002). The pairs of data (n=116) comprising calculated $\theta_v$ and volumetric water content from the MP406 ($\theta_{probe}$) were used to construct a calibration curve, generic to the HBT soil (Figure 4.1). The calibration equation was:

$$\theta_v = 0.981(\theta_{probe}) - 5.1543 \quad r^2=0.77$$

The calibration was then used to convert the $\theta_{probe}$ reading to $\theta_v$.

![Graph showing relationship between volumetric water content and MP406 water content](image)

**Figure 4.1.** Relationship between volumetric water content ($\theta_v$) (%) (calculated from the gravimetric soil water content) and MP406 volumetric water content ($\theta_{probe}$) (%) for the data collected at 10 cm increments down the soil profile collected from 2007 to 2009. The soil profile depth was to 70 cm. Symbols are data points and the line represents the regression equation shown above in the text.
When \( \theta_i \) was measured pre-sowing the location was randomly located within the plots, where \( \theta_i \) was measured after sowing the probe was placed in the seed row and/or between the seed rows (middle). When the surface soil only was measured at depths of 0-6 cm and 6-12 cm, after the 0-6 cm reading the soil was removed by auger to 6 cm and the 6-12 cm reading taken. When \( \theta_i \) was measured to depth to determine profile soil water content the probe was placed in the seed row. In this case the soil was augered to the appropriate depth and the probe then placed in the hole for the reading to be taken, hence depth increments for the soil profile data correspond to the depth at which the probe was placed at 10 cm increments. Each measurement covered a depth of 6 cm, and where profile volumetric water content was calculated the 10 cm increment was used for the calculation. The assumption was that the soil directly below the probe was at a similar water content.

Soil strength was monitored using a hand-held cone penetrometer which measures penetration resistance \( (Q_p) \) (Eijkelkamp, The Netherlands). Measurements were taken at 0-2.5, 2.5-5 and 5-10 cm depth increments. The \( Q_p \) measurements were taken in the same hole consecutively, with the gauge being reset to zero after each preceding measurement.

Across the three years, the soil water and soil strength measurements were taken at one or more of the following periods:

1. from the harvest of the rice crop until sowing to monitor the drying down of the surface soil (soil water only);
2. on the day chickpea was sown;
3. after each plot was sown at intervals from two to four days. Measurements were taken between the sown rows and within the seed row; and
4. when it was deemed no further emergence would occur.

For the 2007 trial, \( \theta_i \) was measured in each plot at sowing to 70 cm depth in 10 cm increments and at flowering and maturity in the PTOS tillage plots to 30 cm depth.

4.2.2 Plant measurements

In all years, the crop was monitored for the dates when 50 % of plants in a plot had flowered, when 50 % of plants in a plot had formed pods, and for crop physiological maturity. Plant
stands after final emergence were counted (2007, whole plot; 2008, 4 rows by 1 m lengths in each plot; 2009, two quadrats per plot 3 rows wide by 1 m length). In 2007, pods on 10 plants were counted at 50 % podding but no samples were taken. In 2008 and 2009 at 50 % podding one quadrat was sampled per plot comprising 2 rows by 1 m or 3 rows by 1 m length, respectively. Final above-ground biomass and grain yields were measured from the whole plot in 2007 and 2008, whilst in 2009, two quadrats per plot were also harvested (3 rows by 1 m length). In addition in 2007, ten plants were selected per plot and above-ground biomass and grain weights determined. Plant growth parameters recorded differed among years and are listed in Table 4.2. For final harvest, plants were cut at ground level and biomass and grain yield determined once the plants had air dried. Pods were removed by traditional farmers’ method of threshing. A traditional bamboo tool was used to separate the pods from the plant. The pods were then sun-dried and then beaten by a stick to break the shell of the pods and separate the grain.

4.2.3 Statistical analysis

Results were analysed using GenStat Release 11.1 (VSN International Ltd, United Kingdom). Differences between means were tested using Analyses of Variance (ANOVA), or where unequal replication of treatment combinations occurred, by Residual Maximum Likelihood (REML). The means, standard error of the means and the least significant differences (l.s.d.) were reported as necessary. Where REML was used the estimated means from the model and the average l.s.d. were reported.
Table 4.2. The chickpea plant parameters measured during crop growth and at harvest for the sowing date experiments established in the High Barind Tract (HBT) of Bangladesh in 2007, 2008 and 2009.

<table>
<thead>
<tr>
<th></th>
<th>Growing season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007-08</td>
</tr>
<tr>
<td><strong>Emergence</strong></td>
<td></td>
</tr>
<tr>
<td>Plant numbers</td>
<td>✓ whole plot ✓ (1 m lengths) ✓ quadrat</td>
</tr>
<tr>
<td><strong>Flowering</strong></td>
<td>✓</td>
</tr>
<tr>
<td>Time to 50 % flowering</td>
<td>✓</td>
</tr>
<tr>
<td>Weight of 10 plants (g)</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Podding</strong></td>
<td>✓</td>
</tr>
<tr>
<td>Time to 50 % podding</td>
<td>✓</td>
</tr>
<tr>
<td>Pods on 10 plants</td>
<td>✓</td>
</tr>
<tr>
<td>Quadrat pod weight (g)</td>
<td></td>
</tr>
<tr>
<td>Quadrat biomass¹ weight (g)</td>
<td>✓</td>
</tr>
<tr>
<td>Plant numbers</td>
<td></td>
</tr>
<tr>
<td><strong>Harvest</strong></td>
<td>✓</td>
</tr>
<tr>
<td>Time to physiological maturity</td>
<td>✓</td>
</tr>
<tr>
<td>Whole plot grain yield (kg)</td>
<td>✓</td>
</tr>
<tr>
<td>Whole plot biomass (kg)</td>
<td>✓</td>
</tr>
<tr>
<td>100 grain weight (g)</td>
<td>✓</td>
</tr>
<tr>
<td>Weight of 10 plants (g)</td>
<td>✓</td>
</tr>
<tr>
<td>Grain weight of 10 plants (g)</td>
<td>✓</td>
</tr>
<tr>
<td>Pods on 10 plants (g)</td>
<td>✓</td>
</tr>
<tr>
<td>Plant numbers</td>
<td>✓ whole plot</td>
</tr>
<tr>
<td>Quadrat biomass weight (g)</td>
<td></td>
</tr>
<tr>
<td>Quadrat pod weight (g)</td>
<td></td>
</tr>
<tr>
<td>Total pod number</td>
<td></td>
</tr>
<tr>
<td>Total number of filled pods</td>
<td></td>
</tr>
</tbody>
</table>

¹Biomass includes all above-ground plant biomass
4.3 Results

4.3.1 Weather

The temperature and rainfall are shown for the 2007, 2008 and 2009 rabi seasons (Figure 4.2). In 2007 and 2008 within-season rainfall was 10.2 and 31.2 mm, respectively; in 2009 there was no within-season rainfall. After sowing of the rabi crop in November (all years) temperatures decreased to December and remained low during January. Maximum temperatures during this period were less than 25 °C and minimum temperatures were as low as 10°C. Temperatures began to rise again during February and reached maxima of 30 °C and above by March. Figure 4.2 also shows the dates of phenological development of all trials completed in 2007, 2008 and 2009 in both this chapter and Chapter 5. For the sowing date trials discussed in this chapter the dates of sowing in the trials are designated by SD1 to SD8 as appropriate; for the tillage type trials discussed in Chapter 5 the date of sowing in the trials are designated by TT. The 2007 trial, which is both a sowing date and tillage type trial, has been designated by SD in the 2007 graph.
Figure 4.2. Weather parameters for the 2007 to 2009 chickpea growing seasons. Daily minimum and maximum temperature (°C) are shown with rainfall (mm). For each trial, the dates of phenological development are shown as symbols on the graph in association with the weather data. Letters on the top of each graph represent the stages of chickpea phenology: S, sowing; E, emergence; FL, flowering; PD, Podding; and PM, physiological maturity. Trials are differentiated by SD, sowing date; and TT, tillage type. The tillage type experiments are described detail in Chapter 5.
4.3.2 Soil water content and soil strength

Following harvest of the previous rice crop, the sowing of the chickpea crop was within the period from 22 November to 22 December for all years. The time of harvest of the previous rice crop and antecedent rainfall and temperature determined the initial surface (0-6 cm) \( \theta_v \), which before the first sowing event was 27 to 34 % (all years). Surface \( \theta_v \) decreased over the sowing period but sowing occurred within the water content range of 21.9 and 33.5 %.

The \( Q_p \) of the surface soil increased with drying of the surface soil and was within the range of 0.36 and 1.9 MPa across the three years. The negative correlation between \( \theta_v \) and \( Q_p \) for the 2008 and 2009 sowing years covers the range from dry to wet in the HBT soil (Figure 4.3). The 2008 and 2009 data at sowing show a similar relationship between \( Q_p \) and \( \theta_v \), therefore both years of data have been included along with the 2009 data collected on the 1 January (10 days after the last sowing) which fills the dry end of the relationship. The linear regression was:

\[
Q_p = 2.277 - 0.0561 \theta_v, \quad r^2 = 0.4279
\]

and is significant \((P < 0.001)\) and shows the soil strength increases as \( \theta_v \) dries in HBT soil (Figure 4.3). The 2007 trial was not included in this analysis as the soil strength measurement was taken directly after sowing.

![Figure 4.3](image_url)

Figure 4.3. Relationship between soil penetration resistance \((Q_p)\) (MPa) and volumetric soil water content \((\theta_v)\) (%) for the 2008 (○) and 2009 (●) chickpea sowing dates and at final emergence counts in 2009 (●). Values are for the surface soil layer of 0-6 cm depth. The line represents the regression equation shown above in the text.
The wettest range of $\theta_v$ at crop establishment was in 2007 (Figure 4.4). The 2007 trial had been irrigated whilst the previous rice crop was awaiting harvest. Therefore soil water content at sowing was higher than usual for this time of year. The 0-6 cm $\theta_v$ was 33.5 % during the first sowing and dried to 27.8 % in the last sowing. In 2008, at crop establishment the $\theta_v$ in the 0-6 cm layer ranged from 21.3 to 28.3 % ($P < 0.01$, l.s.d. 3.57) (Figure 4.5). Soil water did decrease over the sowing period and generally the early sown seeds (22 November to the 28 November) were significantly wetter soil than the later sown seeds (30 November to the 6 December). In 2009, the 0-6 cm soil water layer ranged from 16.9 to 27.4 % ($P < 0.001$, l.s.d. 2.87) and each later sowing date was significantly dryer than that previously sown (Figure 4.6).

In 2008, the $\theta_v$ in the 6-12 cm layer of soil for the most part followed the same drying trend as the surface (Figure 4.5). In 2009, the 6-12 cm layer of soil ranged from 26.6 to 28.3 % and was wetter than the 0-6 cm layer in the last two sowing dates (Figure 4.6).

![Graph](image)

**Figure 4.4.** The mean volumetric soil water content ($\theta_v$) (%) and strength (MPa) of the surface soil in the 2007 time of sowing trial. Soil water was measured at 0-6 cm depth on each sowing date (●) (n =20 to 24) and pre-sowing (○) (n =24 to 28). Soil strength was measured on sowing dates 4, 11 and 14 December at 0-2.5 cm (□), 2.5-5 cm (●), and 5-10 cm (■) depths (n =10 to 24). Error bars indicate ± 1 standard error.
Figure 4.5. The mean soil volumetric water content ($\theta_v$) (%) and strength (MPa) of the surface soil in the 2008 time of sowing trial. Soil water was measured at 0-6 cm (○) and 6-12 cm (●) depth on each sowing date (n = 8). Soil strength was measured at 0-2.5 cm (□), and 2.5-5 cm (■) depths (n = 8). Error bars indicate ± 1 standard error.

Figure 4.6. The mean volumetric soil water content ($\theta_v$) (%) and strength (MPa) of the surface soil in the 2009 time of sowing trial. Soil water was measured at 0-6 cm (○) and 6-12 cm (●) depth on each sowing date (n = 8). Soil strength was measured at 0-2.5 cm (□), 2.5-5 cm (■), and 5-10 cm (■) depths on all sowing dates (n = 8). Error bars indicate ± 1 standard error.
The soil strength increased with later sowing date for all years and was negatively correlated with $\theta_v$ (Figures 4.4, 4.5 and 4.6). In the years with a greater range in $\theta_v$, the difference in soil strength from one sowing date to the next was often significant. The soil strength measurement was taken before sowing in the 2008 and 2009 trials. In 2008, the soil strength in the 0-2.5 cm layer rose from 0.77 MPa at the first sowing to 1.3 MPa, 12 days later (Figure 4.5). A similar rise was seen in the 2.5-5 cm layer which increased from 0.78 to 1.03 MPa. These increases in soil strength over the 12-day period were significant ($P < 0.01$ and $P < 0.05$, respectively) and generally the soil strength of the first four sowing dates were significantly lower than the soil strength of the last three sowing dates. In 2009, both the 0-2.5 and 2.5-5 cm layers showed an increase in soil strength from the first to last sowing (from 0.38 to 1.99 MPa; $P < 0.001$). In 2007, the first soil strength measurement was taken after sowing. The soil strength did not reach the values as high as found in the 2008 and 2009 trials being 0.4, 0.5 and 0.72 MPa across the three depths. In the 0 to 5 cm soil layers, soil strength in 2007 sowing did not increase significantly from the second sowing to the last sowing. In the 5-10 cm soil layer, there was a significant increase from the second and third sowing (0.45 and 0.49 MPa, respectively) to the last sowing date (0.72 MPa) ($P < 0.01$, l.s.d. 0.177). The lower soil strength in the 2007 trial compared with the soil strength in the 2008 and 2009 trials could be attributed to the measurement being taken directly after sowing and the higher soil water conditions in that year.

The surface $\theta_v$ was measured at a time after the last sowing date when chickpea emergence was deemed to be finished. In 2007, the $\theta_v$ was determined 19 days after the last sowing within the seed row and between the seed row. The $\theta_v$ of the 0-6 cm layer measured within the seed row was not different between sowing treatments and at a mean of 29.6 % was only 2.9 % less than the mean at sowing. The 0-6 cm layer of soil between the seed rows had a significantly lower $\theta_v$ in the PTOS (22 %) than the ST (29.5 %) and the ZT (28.3 %) sowing treatments ($P < 0.001$, l.s.d. 2.8). The $\theta_v$ between the rows was not different with sowing date treatment and the mean was 26.6 %. This represents a loss of between 1.2 and 4.6 % from the original $\theta_v$ at sowing.

In 2008, $\theta_v$ of the surface soil in the seed-bed was measured 10 days after the last sowing. The 0-6 cm $\theta_v$ were between 21.8 and 24.7 % and were not different between sowing date
treatments. Soil water had declined by 4% from the first sowing date (22 November) to the 16 December when chickpea plant emergence was counted. The mean $\theta_v$ within the seed row was 23%, whilst between the seed rows the mean was 25%. In 2009, when the $\theta_v$ was determined 10 days after the last sowing date, the mean $\theta_v$ was 13.1% with no significant difference across sowing dates. Between the rows, the $\theta_v$ was higher with a mean of 17.2% at 0-6 cm depth and 23% at 6-12 cm depth. The soil strength was determined at this time and had increased to a mean of 1.5 MPa within the seed row and 2.3 MPa between the seed rows.

The $\theta_v$ of the surface soil in the sown plots was monitored during the period after sowing. This allowed the drying down of the surface layer of soil to be investigated either within or between the seed row. In 2008, the dry down of the plots was only monitored within the seed row and the $\theta_v$ of the pre-sown soils was similar to the $\theta_v$ in the unsown soil (Figure 4.7). In 2009, all locations in the soil had a similar drying pattern (Figure 4.8). The final $\theta_v$ of the 0-6 cm depth of soil was 11 to 13% on 1 January.

![Figure 4.7](image)

**Figure 4.7.** The mean volumetric soil water content ($\theta_v$) (%) of the 2008 time of sowing trial from sowing to final emergence which shows the drying down of the surface soil before and after sowing. Measurements taken were the 0-6 cm depth of the unsown plots (●), and the 0-6 cm (○) depth and 6-12 cm (●) depth of the previously sown plots (n =8 to 24). Error bars indicate ± 1 standard error.
Figure 4.8. The mean volumetric soil water content (θv) (%) of the 2009 time of sowing trial from sowing to final emergence which shows the drying down of the surface soil before and after sowing. Measurements taken were the 0-6 cm (●) and 6-12 cm (○) depth within the seed row, the 0-6 cm (■) and 6-12 cm (□) depth between the seed row, and the 0-6 cm depth in the unsown plots (※) (n =8 to 32). Where visible error bars indicate ± 1 standard error.

In 2008, additional soil strength measurements were taken within the seed row of each previously sown plot at intervals of 2 to 4 days. Figure 4.9 shows these data in addition to the soil strength of the plots sown on that particular date. The soil in the seed rows also had an increase in soil strength with the drying of the soil as previously found in the uncultivated soil. The soil strength in the seed row in the previously sown plots was generally less than the uncultivated soil: maximum soil strength within the seed row after sowing was 0.88, 0.97 and 1.2 MPa with increasing depth from 0 to 10 cm.

In the 2007 trial, the θv was measured in 10 cm increments to 70 cm in the soil profile (Figure 4.10). The mean profile soil water content (SWC) in the 70 cm profile was 184 mm. In the surface 30 cm, 79 mm of profile SWC was held. At flowering and maturity, this had dropped to 25 and 29 mm, respectively. The θv in the soil profile did not differ with each sowing date.
Figure 4.9. The mean soil strength (MPa) in the 2008 time of sowing trial measured at two-day intervals from the 22 November to the 4 December. Soil strength was measured before sowing in the uncultivated soil at depth of 0-2.5 cm (■) and 2.5-5 cm (■). Soil strength was measured in the previously sown plots within the seed row at 0-2.5 cm (○), 2.5-5 cm (●) and 5-10 cm (●) depth. Error bars indicate ± 1 standard error.

Figure 4.10. The volumetric soil water content ($\theta_v$) (%) at 10 cm depth increments at each sowing date to 70 cm and at flowering and maturity to 30 cm (n =12 to 24) for the 2007 time of sowing trial. Error bars indicate ± 1 standard error.
4.3.3 Plant numbers at emergence and throughout the growing season

The previous section quantified the decline in \( \theta_v \) with successive sowings. Plant numbers are reported in Figure 4.11. Chickpea plants were counted when emergence was deemed to have finished in all trials, at pod formation in 2009, and at harvest in 2007 and 2009. Sowing rates of 38 to 45 kg/ha were used with the aim of creating a plant stand of about 20 plants/m². In the 2007 sowing, the number of emerged plants was between 9 and 29 plant/m². Overall the total emergence decreased with tillage type from PTOS to ST to ZT \((P <0.001, \text{l.s.d. 3.14})\). Significant interactions were found across the tillage treatments at the different sowing dates in respect to emergence \((P <0.001, \text{l.s.d. 6.29})\); this was most apparent in the first and last sowing dates. The emergence of plants sown on the first and last sowing date, when \( \theta_v \) was 35 and 28.6 %, respectively, was greater in the PTOS tillage treatment \((P <0.01, \text{l.s.d. 3.63})\).

In 2008 and 2009, the emergence of the chickpeas across the sowing dates showed no trend with sowing date (Figure 4.11) nor therefore with changes in \( \theta_v \). For all sowing dates in the 2008 and 2009 trials, the mean number of plants emerged was above the target of 20 plants/m². The final number of plants emerged in the 2007 sowing, \(17 \pm 1.08\) plants/m², was less than the mean number of plants in 2008 and 2009 sowings (35 and 28 plant/m², respectively).

There was minimal decrease in plant population density from emergence to harvest in 2007, indicating there was no major plant loss during the season. In 2009, the plant population within a particular sowing date showed greater variation between counts at emergence, podding and harvest. This variation resulted in an increase in plant population at maturity which may in part be attributed to sampling of new quadrats for the final sampling time.
Figure 4.11. The mean plant population (plants/m²) at various times during the chickpea growth for: a) the 2007 trial at emergence (full bar) and harvest (hatched bar) for each sowing date and tillage treatment viz., power tiller operated seeder (PTOS), strip tillage (ST) and zero tillage (ZT); b) during the 2008 trial at emergence for each sowing date; and c) in 2009 at emergence (grey bar), podding (black bar) and harvest (hatched bar) for each sowing date. Error bars indicate 1 standard error.
4.3.4 Chickpea growth and yield

There were no apparent constraints due to disease (BGM, collar rot, wilt), insect (pod-borer) or weeds in these trials, due to effective control measures (Table 4.1). These constraints, which commonly affect chickpea crops in the HBT, can interact with sowing date. Thus in the present study, sowing date effects can be uniquely attributed to soil and weather conditions. In each year the same machinery operator sowed all treatments to minimise any effect of operator technique and experience.

4.3.4.1 2007

The growth stages of the 2007 chickpea time of sowing trial are presented in Table 4.3. At flowering in 2007 the chickpea biomass per plant was between 2.5 and 4.7 g/plant, whilst at harvest it was between 2.7 and 8.8 g/plant (Figure 4.12). At flowering, tillage treatment had no effect on plant biomass, however the 7 December sowing had the greatest mean biomass ($P <0.001$, l.s.d. 7.17). By harvest there was no longer an effect of sowing date on plant biomass, but the PTOS plots had less biomass than the other tillage treatments. After podding and at harvest the number of pods per plant was counted. There was very little difference in the number of pods per plants at these two measurement times (Figure 4.13). At both times there were fewer pods per plant in the PTOS tillage type than the other tillage treatments and the 14 December sowing had fewer pods per plant than the 1 and 7 December sowings.

<table>
<thead>
<tr>
<th>Plant phenology</th>
<th>Sowing date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Dec</td>
</tr>
<tr>
<td>50 % flowering</td>
<td>11 Feb (72)</td>
</tr>
<tr>
<td>50 % podding</td>
<td>22 Feb (81)</td>
</tr>
<tr>
<td>Crop physiological maturity</td>
<td>2 Apr (124)</td>
</tr>
</tbody>
</table>

1 Number in parentheses refers to the number of days after sowing (DAS)

Table 4.3. Phenology of crop development of the chickpea in the 2007 time of sowing trial in Rajshahi, Bangladesh.
Figure 4.12. The mean weight per plant (g) at flowering (full bar) and harvest (hatched bar) for the 2007 time of sowing trial for each sowing date and tillage treatment viz, power tiller operated seeder (PTOS), strip tillage (ST) and zero tillage (ZT). Error bars indicate 1 standard error.

Figure 4.13. The mean pod number per plant at podding (full bar) and harvest (hatched bar) for the 2007 time of sowing trial for each sowing date and tillage treatment viz, power tiller operated seeder (PTOS), strip tillage (ST) and zero tillage (ZT). Error bars indicate 1 standard error.

At harvest the whole plot biomass, grain weight, pod number and biomass per plant were also less in the PTOS than in the ZT and ST. Whole plot grain yield however showed no such trend (Figure 4.14). The final whole plot harvest grain yield and biomass suggest 7 December sowing had less yield than 1, 11 and 14 December sowings. The other plant parameters
measured at final harvest such as pod number and grain weight per plants suggested 14 December sowing was decreased relative to earlier sowing dates (Figure 4.15).

Chickpea growth parameters measured within the season and at final harvest consistently showed that the PTOS tillage treatment has less biomass and yield that the ST and ZT treatments. Sowing date had a variable effect in that the parameters which relate to biomass and grain yield per plant were less for 14 December sowing than all other sowing dates. Whereas, when the whole plot harvest was considered the grain yield and biomass for 7 December sowing was less than all others.

Figure 4.14. The mean grain yield (kg/ha) (full bar) and above-ground biomass (kg/ha) (hatched bar) of the 2007 time of sowing trial for each sowing date and tillage treatment viz, power tiller operated seeder (PTOS), strip tillage (ST) and zero tillage (ZT). Measurements were taken from the whole plot. Error bars indicate 1 standard error.
Figure 4.15. The mean grain weight per plant (g) at harvest of the 2007 time of sowing trial for each sowing date and tillage treatment viz., power tiller operated seeder (PTOS), strip tillage (ST) and zero tillage (ZT). Error bars indicate 1 standard error.

4.3.4.2 2008

The growth stages of the 2008 chickpea time of sowing trial are presented in Table 4.4. At podding, the chickpea plant biomass was not different across the sowing dates, however pod weight was less in the later sown treatments (Table 4.5). Since all plots were sampled on the same date the lower yield could be an effect of fewer pods developed because the growing period was shorter for the later sown dates. There was an increase in final grain yield and biomass from the first sowing date (22 November) to 30 November after which both grain yield and biomass decreased for the final two sowing dates. Generally, the yield and biomass of the sowing date of the 2 December was significantly greater than the three earliest and two latest sowing dates.
Table 4.4. Phenology of crop development of the chickpea in the 2008 time of sowing trial in Rajshahi, Bangladesh.

<table>
<thead>
<tr>
<th>Plant phenology</th>
<th>22 Nov</th>
<th>24 Nov</th>
<th>26 Nov</th>
<th>28 Nov</th>
<th>30 Nov</th>
<th>2 Dec</th>
<th>4 Dec</th>
<th>6 Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergence date</td>
<td>30 Nov (8)</td>
<td>1 Dec (7)</td>
<td>4 Dec (8)</td>
<td>6 Dec (8)</td>
<td>8 Dec (8)</td>
<td>10 Dec (8)</td>
<td>12 Dec (8)</td>
<td>14 Dec (8)</td>
</tr>
<tr>
<td>50 % flowering</td>
<td>18 Jan (57)</td>
<td>18 Jan (55)</td>
<td>21 Jan (56)</td>
<td>21 Jan (54)</td>
<td>25 Jan (54)</td>
<td>25 Jan (54)</td>
<td>28 Jan (55)</td>
<td>30 Jan (55)</td>
</tr>
<tr>
<td>50 % podding</td>
<td>23 Jan (62)</td>
<td>23 Jan (60)</td>
<td>27 Jan (62)</td>
<td>27 Jan (60)</td>
<td>31 Jan (60)</td>
<td>31 Jan (60)</td>
<td>3 Feb (61)</td>
<td>5 Feb (61)</td>
</tr>
<tr>
<td>Crop physiological maturity</td>
<td>21 Mar (119)</td>
<td>21 Mar (119)</td>
<td>21 Mar (119)</td>
<td>21 Mar (119)</td>
<td>21 Mar (119)</td>
<td>21 Mar (119)</td>
<td>21 Mar (119)</td>
<td>21 Mar (119)</td>
</tr>
<tr>
<td>Crop harvest</td>
<td>4 April all sowing dates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Number in parentheses refers to the number of days after sowing (DAS)
2 Not recorded

Table 4.5. The chickpea crop growth parameters for the 2008 time of sowing trial.

<table>
<thead>
<tr>
<th>Sowing date</th>
<th>Above-ground biomass at 50 % podding (g/m²)</th>
<th>Pod weight at 50 % podding (g/m²)</th>
<th>Grain yield (kg/ha)</th>
<th>Above-ground biomass at harvest (kg/ha)</th>
<th>Harvest index</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 Nov</td>
<td>122.3</td>
<td>89.3abc</td>
<td>350ab</td>
<td>761ab</td>
<td>0.42</td>
</tr>
<tr>
<td>24 Nov</td>
<td>137.1</td>
<td>101.2a</td>
<td>425ab</td>
<td>872ab</td>
<td>0.49</td>
</tr>
<tr>
<td>26 Nov</td>
<td>133.8</td>
<td>99.3a</td>
<td>351ab</td>
<td>833ab</td>
<td>0.41</td>
</tr>
<tr>
<td>28 Nov</td>
<td>122.5</td>
<td>77.5abc</td>
<td>485abc</td>
<td>972abc</td>
<td>0.49</td>
</tr>
<tr>
<td>30 Nov</td>
<td>156.7</td>
<td>77.7abc</td>
<td>527ac</td>
<td>1066ac</td>
<td>0.49</td>
</tr>
<tr>
<td>2 Dec</td>
<td>136.3</td>
<td>59.5cd</td>
<td>679c</td>
<td>1362c</td>
<td>0.49</td>
</tr>
<tr>
<td>4 Dec</td>
<td>116.3</td>
<td>48.8bd</td>
<td>287b</td>
<td>613b</td>
<td>0.46</td>
</tr>
<tr>
<td>6 Dec</td>
<td>119.5</td>
<td>37.1d</td>
<td>427b</td>
<td>915ab</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Mean l.s.d. n.s. 35.8 224 392 n.s. 1.4

Linear mixed model (REML) P-value 0.007 0.052 0.039

n.s. indicates no significant difference
l.s.d. indicates the least significant difference at P<0.05
Means in a column with the same superscripts are not significantly different at P<0.05

4.3.4.3 2009

The growth stages of the 2009 chickpea time of sowing trial are presented in Table 4.6. During the growing season, the above-ground biomass and pod weight at 50 % podding was less in the fourth sowing date than the previous three sowing dates (P<0.01) (Figure 4.16). However, since all plots were sampled on the same date the growing period was shorter for the later sown dates. At final harvest, the above-ground biomass and pod weight measured in quadrats was greater in the treatments sown on 3 and 6 December than those sown on the 14
and 22 December ($P < 0.01$ and $P < 0.001$, respectively) (Figure 4.17). In 2009, the highest grain yield at 775 kg/ha was from the chickpea sown on 6 December (Figure 4.19) but the 3 and 6 December sown crops were not different in grain yield. Of the later sowing dates, the chickpea sown on the 14 December had grain yield significantly less than the 3 December sowing date, and those sown on the 22 December had grain yield significantly different to both the 3 and 6 December sowing dates. Pod numbers were less in the 14 and 22 December sowing dates than the previous two, and the percentage of unfilled pods increased from 10 to 28 % with the later sowing date (Figure 4.18). The whole plot harvest results showed no difference in total biomass of the chickpea plants across sowing dates.

### Table 4.6. Phenology of crop development of the chickpea in the 2009 time of sowing trial in Rajshahi, Bangladesh.

<table>
<thead>
<tr>
<th>Plant phenology</th>
<th>Sowing date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 Dec</td>
</tr>
<tr>
<td>50 % flowering</td>
<td>15 Feb (74)</td>
</tr>
<tr>
<td>50 % podding</td>
<td>22 Feb (81)</td>
</tr>
<tr>
<td>Crop physiological maturity</td>
<td>1 Apr (119)</td>
</tr>
<tr>
<td>Crop harvest</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1Number in parentheses refers to the number of days after sowing (DAS)

![Figure 4.16](image_url)

Figure 4.16. The mean above-ground biomass (g/m$^2$) (filled bar) and pod weight (g/m$^2$) (hatched bar) of the quadrats measured at podding of the 2009 sowing date trial. Error bars indicate 1 least significant difference (l.s.d.) at the $P < 0.05$. 
Figure 4.17. The mean above-ground biomass (g/m$^2$) (filled bar) and pod weight (g/m$^2$) (hatched bar) of the quadrats measured at harvest of the 2009 sowing date trial. Error bars indicate 1 least significant difference (l.s.d.) at $P<0.05$.

Figure 4.18. The mean number of total pods (number/m$^2$) (filled bar) and filled pods (hatched bar) of the quadrats measured at harvest of the 2009 sowing date trial. Error bars indicate 1 least significant difference (l.s.d.) at $P<0.05$. 
Figure 4.19. The mean grain weight (kg/ha) (filled bar) and plant biomass (kg/ha) (hatched bar) of the whole plot at harvest of the 2009 sowing date trial. Error bars indicate 1 least significant difference (l.s.d.) at $P<0.05$.

4.4 Discussion

4.4.1 Drying pattern of surface soil

In the HBT, chickpea crops are often at low plant densities in farmers’ fields due to a number of factors including: a low seed rate, poor seed viability, inadequate germination and emergence, and high seedling mortality caused by disease, insects, vermin or drought (Khanna-Chopra and Sinha 1987; Musa et al. 2001; Johansen et al. 2008b). Low seed rate, poor seed viability and high seed mortality can be addressed by agronomic management, seed testing and seed storage techniques which would all assist in obtaining adequate plant stands for the environmental conditions. In the broadcast system of sowing, the seed rate has been set to obtain 33 plants/m$^2$ (Saxena 1980a, 1987; Ali et al. 2007). In Bangladesh generally, a seed rate of 37.5 kg/ha will achieve plant stands of between 18 to 32 plants/m$^2$ using broadcast seeding and full tillage (Johansen et al. 2008a). In the present work, the soil physical properties of soil water and soil strength were investigated to identify reasons for inadequate germination and emergence of chickpea that can occur in the farmers’ fields. Specifically poor crop establishment is often blamed on the rapid surface soil drying conditions of the HBT which can also occur across Bangladesh and South Asia (Musa et al. 2001). Despite the frequent assertion
that poor chickpea establishment is caused by a drying seed-bed, no soil water values during this period have been documented. Conclusions about drying soil conditions are based on observations of soil conditions and crop establishment under traditional broadcast-sowing techniques with full soil tillage. The traditional method of sowing by a bullock-drawn country plough required at least two passes of the field to create a seed-bed: initially one or more passes are required to incorporate the hand broadcast seed and fertiliser and subsequent passes are required to level the field (Johansen et al. 2008a). This method is slower in comparison to one-pass with the power tiller.

The measurements of $\theta_e$ in 2007, 2008 and 2009 during sowing by minimum tillage techniques show a loss of 7 to 10 % from first to final sowing. When this drying period is extended to include final emergence of the chickpea (which may potentially be one month after the rice harvest) only in 2009 was the $\theta_e$ of the surface soil at values established in Chapter 3 to be limiting to chickpea establishment. Surface soil water contents as low as this would be an impediment to the chickpea crop establishment, however such late sowing of chickpea is not recommended as the agronomic growth requirements of the chickpea at flowering and pod-filling stages would not be met. The optimum period within which chickpea can be sown is not only dependent on the soil water content but also on the agronomic requirements of the chickpea plant during the periods of vegetative and reproductive growth (Saxena 1987). In the HBT of Bangladesh, this means that chickpeas are best sown before 15 December (Johansen et al. 2008b); after this time low initial temperatures cause poor early growth, which limits root growth and makes the crop susceptible to terminal drought. A drop in yield is then likely under late season high temperatures and receding profile soil water content which leads to forced maturity and/or terminal drought (Chaturvedi and Ali 2004; Canci and Toker 2009).

4.4.2 The effect of soil physical properties in the seed-bed on chickpea emergence

In pot trials, reported in Chapter 3, soil water content, soil bulk density and soil strength were investigated under laboratory conditions. Emergence of chickpea in HBT soils was most successful, when rate and percentage emergence were both considered, between gravimetric water contents ($\theta_g$) of 16 and of 21 %. There was delayed emergence as $\theta_g$ decreased from 16 to
12 % or when it increased from 21 to 23 % but no emergence was recorded at \( \theta_g \) wetter or drier than these limits. In comparison, the field conditions from 2007 to 2009 at sowing in the HBT of Bangladesh had surface \( \theta_g \) between 12 and 24 %. Emergence occurred in all years across all \( \theta_g \), and was always within the range where emergence was found to be successful, although at times it was delayed. There was no correlation between soil water content and plant population at emergence across the three years of the study. Given that the soil water contents were within optimum ranges, this was not surprising.

Soil water contents at field capacity, 36 % \( \theta_g \) at 10 kPa, were not optimum for chickpea emergence in the HBT soils (Chapter 3). For successful emergence under field conditions in these soils the range of water content was from two-thirds to one-third of field capacity water content. Similarly in a black Vertisol soil (field capacity 32 %) of central India, emergence of chickpea was found to be optimum at \( \theta_g \) of 23 to 26 %, (81 % of field capacity) but fell significantly at 20 % \( \theta_g \) (62 % of field capacity). In addition across the genotypes tested, some were more tolerant of soil water contents of 20 % with small seeded desi type chickpea genotypes having greater tolerance than large seeded kabuli types (Saxena et al. 1983).

Seedling emergence can also be limited due to soil strength which restricts the elongation and penetration of shoots and roots (Nasr and Selles 1995). Where initial seedling growth is unimpeded, roots will be able to penetrate deeper into the profile to access water and nutrients, increasing early crop growth and final grain yields (Johansen et al. 1997). In the present field trials, soil strength covered the range from 0.35 to 1.9 MPa before sowing across all depths. Soil strength increased with depth from 0-10 cm. Post-sowing in the seed row, the soil strength was lower and in the 0-5 cm depth range reached a maximum of 0.97 MPa. At 10 cm depth the maximum soil strength was 1.2 MPa. In pot trials (see Chapter 3), where chickpea shoots met soil strength of 0.58 MPa as a uniform barrier the shoot found a path between the zones of high strength through which elongation occurred. Where the soil was finely aggregated and did not register a soil strength reading the shoots were not limited in their emergence. Chickpea seedlings have been found to exert more force to push through surface crusts by increasing their epigeal diameter (Sivaprasad and Sundara Sarma 1987). In field conditions the shoots were not
limited in emergence due to soil strength as they were able to penetrate through the voids between aggregates.

In pot trials (see Chapter 3) as soil strength increased from 0.6 to 1.3 MPa, root growth declined; at 1.2 MPa, root elongation had reduced by half. Tillage of the plots in the field trials decreased the soil strength in the seed row, directly after sowing even in strip and zero tillage. Soil strength did increase with depth and although at all depths root growth may be inhibited, as demonstrated in the pot trials in Chapter 3, root growth would not be completely restricted. Root growth is prevented between 2 to 3.7 MPa depending on species (Kirkegaard et al. 1992). With depth, the soil layer most likely to restrict root growth would be at 10-15 cm depth. This is where a hard pan normally develops in these soils due to the puddling and cultivation required for rice establishment in the kharif season (Johansen et al. 2008b). Although not measured in the present study at 10-15 cm depth the values of soil strength would probably be higher than levels found at the 5-10 cm depth of the pre-sowing measurements. Once the seedlings roots have grown through the tilled surface layers of lower soil strength they would have to penetrate this hard pan. Musa et al. (2001) suggested that root penetration through the hard pan should not be limited so long as this layer has not dried out. However, no direct evidence of this has been produced.

4.4.3 Effect of sowing method on seed-bed soil water content and emergence

The 2007 trial covered the wettest range in water contents and had lower emergence across all $\theta_v$ compared to the 2008 and 2009 trials. As $\theta_v$ decreased with later sowing dates to the levels seen in the 2008 and 2009 years, the numbers of plants that emerged in 2007 did not increase. This suggests that in 2007 at the later sowing dates there were limitations to chickpea emergence other than $\theta_v$.

In the 2007 trial, the PTOS had a greater seedling emergence than the ZT and ST. At the time of sowing, observations of seed dropping (by the machine operator and participating scientists) suggest that the seed drop was more consistent in the PTOS than the ST and ZT systems, leading to more seeds per area being dropped in the PTOS. The PTOS seemed to be better suited to emergence of the chickpea seeds at the wetter $\theta_v$ than the other tillage types due
to the combination of consistency of seed drop, adequate seed coverage by fine aggregate soil and less smearing of the furrow wall. A seed with poor contact with the soil will need to imbibe water from the vapour phase (Wuest et al. 1999), which may not produce an adequate supply of water in situations of open furrows and coarse aggregation of the soil above the seed, allowing air flow and evaporation. In these conditions, the seed-soil contact in the ST and ZT methods may be less than the PTOS.

The drying of the surface soils between the seed rows was greater in the PTOS compared to the other tillage types in 2007 (Figure 4.4). With PTOS the inter-row was a tilled layer of soil, while with ST or ZT the inter-row was less disturbed. The greater drying of the tilled layer in the inter-row of STSP suggests that the tillage increased surface evaporation.

4.4.4 Crop growth

When the relationship between grain yield and sowing date was examined for the three years of trials there was an increase in mean grain yield with sowing date from 22 November until 1 December, consistent high yield with sowing between 1 and 10 December and decreased grain yield with further delays in sowing (Figure 4.20). Figure 4.20 combines three years of the time of sowing trials including the variation in tillage technique in 2007, and the differences in seed and fertiliser rate. These differences in management and season have impacted on the grain yield in the different years. The soil water contents at sowing were not limiting to chickpea crop establishment and only with different tillage type was final emergence different in any year.
Figure 4.20. The mean grain yield (kg/ha) for the different sowing dates over the three seasons (2007, 2008, 2009). This includes the data for variation in tillage technique in 2007 although each tillage type is not differentiated. Error bars indicate ± 1 standard error.

Other researchers have found that although chickpea yields peak with late November sowing, delayed sowing up to early December will still give satisfactory yields but thereafter yield penalties of 9 to 38 % arise from sowing delayed to 30 December (Kabir et al. 2009; Ahmed et al. 2011). A series of on-farm field trials run from 1999 to 2002 examined the effect of seed priming on chickpea crops in the HBT (Musa et al. 2001). Johansen et al. (2008b) compiled this data to investigate the effect of sowing date on chickpea yields in the HBT. As sowing dates changed from early November to late December there was a declining trend in chickpea yield. However, the data also showed that the yields were variable across sowing dates and seasons, with low yields in early sown crops and high yields in later sown crops. In the current trials from 2007 to 2009, the yields show a trend towards greater yields from early November to early December sowing, but there is also variability in grain yields between the years and sowing date. Johansen et al. (2008b) concluded that the combination of good agronomic management and adequate soil moisture will allow adequate yields within a quite wide sowing window. In the current system of mechanised row-sowing, the early sown crops in 2008 did show a lower yield than the later sown crops, and this trend is opposite to the relationship of the data presented in Johansen et al. (2008b) where the highest yields were
obtained from the earlier sowing dates. A difference between the current trials and the on-farm data collected by Musa et al. (2001) are that the latter were sown with broadcasting of the seed and fertiliser following full tillage and laddering. This method requires greater time to prepare and sow the land, leading to drying surface soils and delayed emergence and slow seedling growth due to low temperatures (Johansen et al. 2008b). The current time of sowing trials were all sown by 2WT-mounted planters which allows the seed and fertiliser to be placed together in a furrow and which can provide a more even soil coverage of the seed in one-pass of the machine. These conditions were not limiting to chickpea establishment, and the crops sown earlier avoided low temperatures during early seedling growth. However, sowing date, soil water content at sowing and the vigour of the emerged plants are not the only indicators of potential yield. The differences in final yield of chickpea crops may also be attributed to conditions faced later in the season, such as: the rate of plant water use, in-season rainfall and temperatures, biotic stresses (BGM, pod-borer, collar rot), nutrient deficiencies, and effectiveness of nodulation.

The three years of data demonstrate the morphological plasticity of the indeterminate chickpea crop in the HBT. Chickpea plants are often able to compensate for lower plant numbers by better growth of the remaining plants (Saxena 1979). Evidence of plasticity of growth is more apparent in the 2007 trial where plant numbers in the PTOS plots were greater than in the ST and ZT treatments. In the present study chickpea plants compensated for lower plant numbers in the ZT and ST treatments than the PTOS through greater biomass and pods per plant (Saxena and Sheldrake 1974; Siddique et al. 1984). This greater accumulation of biomass occurred after the time of 50% flowering.

Another example of morphological plasticity in chickpea production is illustrated by the 2007 trial where the plant numbers were less than the 2008 and 2009 trials but grain yields were in the higher range of all yields. However, apart from plasticity of plant growth the effects of sowing time, temperature and soil water content on plant growth later in the season need to be considered. The ability of the chickpea plants in the 2007 trial to compensate for low plant numbers may also be associated with the additional water in the surface soil, due to the irrigation which occurred before sowing.
The last sowing date in 2007 was just before the recommended cut off date for sowing chickpeas in the HBT and yet there was no detrimental effect on final yield. The wetness of the 2007 field before sowing compared to sowing in 2008 and 2009 apparently protected the crop from water stress as shown by the relatively high yields of all treatment in 2007 (Figure 4.20). At sowing in 2007, the soil stored a mean of 158 mm of water in the surface 60 cm of the soil profile. By contrast, at the 2009 sowing the soil stored a mean of 126 mm of water in the top 60 cm of the profile. The additional 32 mm of water in the soil profile in 2007 was associated with 185 kg/ha extra grain yield. An indicator that the chickpea plants compensated for low plant numbers through modifications to plant growth was the difference in pods per plant in the 2007 compared to 2009 trial (Saxena 1979). The mean number of pods per plant in the 2007 trial was 37, whilst in the 2009 trial the mean number of pods per plant was 21.

4.4.5 The effect of weather parameters on crop growth

Grain yield in the time of sowing trials was affected by the soil conditions at sowing through the influence on final plant numbers and the vigour of early seedling growth. However, the conditions during the season such as fog incidence, rainfall, maximum and minimum temperatures, day length and soil profile water supply can influence the vegetative and reproductive development of the plant (Roberts et al. 1980; Deshmukh et al. 2004; Ahmed et al. 2011). Fog and low temperatures during early growth can lead to poor seedling growth, while high temperatures at maturity lead to enforced maturity and low or no in-season rainfall can lead to a decline in soil profile reserves of water which cause terminal drought (Deshmukh et al. 2004). Increased day length and high temperatures can induce maturity and decrease grain yields (Ahmed et al. 2011). In addition weeds, BGM disease and pod-borer need to be controlled.

The duration of each phenological growth stage decreased with sowing date within all years. In 2007 the decrease was by 7 to 10 days, whilst in 2008 and 2009 only 2 to 5 days decrease occurred from first to last sowing. The range in sowing days was 13, 14 and 19 days, respectively, for 2007, 2008 and 2009. Day lengths will begin to increase on 21 December, so the majority of chickpea growth is under increasing day lengths. The range in sowing dates
means later sown chickpea was under longer day lengths at all growth stages than earlier sown chickpea. Increased day length can enhance flowering and reduce vegetative growth (Roberts et al. 1980; Ahmed et al. 2011). Ahmed et al. (2011) reported a decrease of 5 to 8 days for reproductive growth for sowing dates from 10 November and 30 November, similar to our decrease in duration of the growth stage. When the range in sowing dates extended to 30 December, this decrease in growth duration was 19 to 21 days for reproductive growth and 33 days for maturity. The combination of increased day length during reproductive growth (which occurs with later sowing date), and high temperatures induces earlier maturity and decreases grain yields (Ahmed et al. 2011). Ahmed et al. (2011) attributed yield differences to day length and increased temperature only after 10 December sowings, when the range from the first to last sowing date was >30 days.

In 2008, the first crop was sown early and the last was sown before the recommended cut-off date, covering a 14 day range. In itself the 2008 data shows a relationship between grain yield and sowing date with grain yield increasing with each successive sowing date until the last two sowings where grain yield fell by 252 to 392 kg/ha. Lower yields may be associated with the number of days when the minimum temperature was below 15 °C during the reproductive phase of chickpea growth. Flowering can be indeterminate when temperatures are less than 14 to 16 °C and pod formation delayed at 16 °C, and prevented at 10 to 12 °C (Croser et al. 2003; Berger et al. 2004). In India, it has been reported that poor pod set can occur when day temperatures are <20 °C and night temperatures <10 °C (Saxena 1980b; Saxena and Johansen 1988; Saxena et al. 1988; Kumar et al. 2010). Minimum temperatures can be a factor in preventing pod set from flowers (Saxena 1980b). For the 2008 sown crop, from 15 January to 20 February, the minimum temperature was between 13 and 15 °C. For the 1st sowing date, this corresponded to 34 days after 50 % flowering when the crop experienced minimum temperatures of 13 to 15 °C, whilst for the 6th sowing date only 27 days of this growth phase were at such low temperatures. Whilst the minimum temperatures did not reach the threshold that is proposed to limit reproductive growth the increased numbers of days with minimum temperatures below 15 °C may have increased loss of flowers and limited pod production (Rahman et al. 2000; Clarke and Siddique 2004; Toker et al. 2007). With delayed sowing from
22 November to 2 December, grain yields increased incrementally. This may be because the later sown crops experienced fewer days at minimum temperatures that delay flowering and pod formation, than the early sowing dates.

The final two sowing dates in 2008, 4 and 6 December, did not follow the above trend in yields. Both pod weight at 50% podding and grain yield were less than the previous sowing dates. Emergence of these two latest sowing dates in 2008 occurred when maximum temperatures dropped over a period of 10 days from 30 °C to a low of 17 °C, before stabilizing again at 25 °C (Figure 4.2). Moreover, in those treatments plants had reduced growth and vigour, symptoms commonly reported in the region at low temperatures (Johansen et al. 2008b). A combination of low temperatures at initial crop growth and high temperatures during podding may explain the low yields for the last two sowing dates in 2008 (Summerfield et al. 1984; Rahman et al. 2000).

The 2009 trial was sown late, indeed the final sowing date was seven days after the recommended cut off for chickpea. The grain yields for the first two sowing dates were high whilst the last two sowing dates which were sown close to and seven days after the recommended last sowing date, respectively, had greatly reduced grain yields. Early crop growth was less vigorous in the later sown crops than the early sown crops. The maximum and minimum temperatures during the 2008 and 2009 seasons provide some indication as to why crop yields vary with sowing date and between seasons.

In the 2009 season, from sowing to podding the mean maximum and minimum temperatures (23/12 °C) are lower than the 2008 year (25/15 °C) (Figure 4.2). These lower mean temperatures in 2009 have increased the time to flowering and podding, respectively, from 57 and 62 days in 2008 to 73 and 79 days in 2009, for the first sowing dates in each year. In addition to this, the average maximum and minimum temperatures in the 2009 year from podding to maturity were greater by 3 and 2 °C, respectively. For the period from the beginning of March to maturity there was an increase from 30 °C in 2008 to 33 °C in 2009 in mean maximum temperature. Day and night temperatures of 35 °C and 18 °C, respectively have been found to decrease chickpea yields compared to 30 °C day and 10 °C night temperatures (Summerfield et al. 1981; Kumar and Abbo 2001).
During the last 47 days of chickpea growth in the 2009 sowing, the mean maximum temperature was 36 °C, by contrast with the 2008 sown crop which experienced mean maximum temperature of 30 °C over the same time period. High temperatures (35 °C) at flowering affect pod formation, whilst high temperatures during pod development affect the number and weight of seeds (Wang et al. 2006). The last two sowing dates of 2009 were exposed to high temperatures for a longer period of their reproductive growth phase than the early sowing dates of the same year. The lower yields of the latest two sowing dates in 2009 may be explained by the greater exposure to both the low temperatures in the early stages of growth (sowing to podding) and high temperatures from podding to maturity (Summerfield et al. 1984; Saxena et al. 1988; Rahman et al. 2000). Evidence of these weather characteristics affecting the growth of chickpea in 2009 comes from the percentage of unfilled pods which increased with later sowing dates, from 10 % for the 3 December sowing to 28 % for the 22 December sowing in 2009 (Wang et al. 2006). The 2008 and 2009 chickpea crops both had the same total range of days from sowing to maturity, 116 to 119 days. However, in 2009 chickpea took longer to flower than in 2008, but had a shortened reproductive growth phase. The number of days from podding to maturity in the 2009 sown crop was 38 to 40 days whilst in the 2008 sown crop it was 55 to 57 days. The duration of reproductive growth has been found to decrease with temperature increases, both the minimum and maximum, in controlled experiments, but the additional days of growth in the reproductive phase under the lower temperature do not always translate into higher yields (Roberts et al. 1980). This may explain why the two early sowing dates in 2009 have yields similar to those in the 2008 year even though there were 15 more days of reproductive growth in 2008.

4.5 Conclusion

Under mechanised row-sowing over three planting seasons, soil strength and soil water content did not limit chickpea establishment from early November to late December in the HBT of Bangladesh. Soil water contents in the surface remained at values that would not limit chickpea establishment until well beyond the latest sowing date that would avoid limiting weather conditions at later growth stages.
In the 2007 to 2009 trials the soil water content in the seed-bed after broadcast and mechanised row-sowing with a 2WT-mounted planter remained within the range of wilting point and field capacity for the HBT soil as determined in Chapter 3. Non-limited chickpea crop establishment occurs close to the soil water content at wilting point and within one-third of the soil water content at field capacity in HBT soils. At most sowing dates during the 2007 to 2009 field trials the soil water content was found to be at high soil water contents, closer to field capacity than wilting point. Whilst the soil water content and soil strength were not limiting to crop establishment, other soil structure characteristics within the seed-bed may limit or delay chickpea crop establishment at these high soil water contents under mechanised row-sowing. The effect of different minimum tillage techniques on the resultant soil structure in the seed-bed (aggregates size, seed-soil contact, furrow surface characteristics) are further investigated in Chapter 5.

Considering the grain yields for 2007, 2008 and 2009 sowing, the optimum sowing time by 2WT-mounted planter was between 30 November and 10 December. The recommended cut off time for sowing of chickpea crops in the HBT, based on previous studies with conventional broadcast seeding and full tillage, remains valid for mechanised row-sowing.

When the conditions at sowing are not limiting to chickpea establishment, grain yields are then determined by vegetative and reproductive growth within the season. Across the sowing window (30 November to 10 December) the small differences in day length will have little effect on crop phenology. However, minimum and maximum temperatures will vary from year to year during the sowing window and in the present study the timing and duration of lower temperatures early in the growing season and hotter temperatures later in the growing season altered the duration of vegetative and reproductive growth. There is also evidence in the 2008 trial that extended periods of cooler temperatures (minimums <15 °C) during flowering may have led to loss of flowers and limited pod production. When later sown chickpea experienced high temperatures for longer periods during reproductive growth, yield loss occurred as evidenced by a larger percentage of empty pods (2009 trial).

Adjustments in the time of sowing which are feasible with mechanised row-sowing may allow farmers to avoid periods of low temperature which decrease vigour during early seedling
growth and increase the duration of the vegetative growth phase and also avoid the onset and duration of high temperatures later in the season. Mechanised row-sowing appears to offer greater control over sowing time for chickpea and other rabi season crops which in turn should improve both crop establishment and later crop growth.
5 The effect of tillage type on initial seed-bed soil water content and chickpea yields

5.1 Introduction

The traditional method of sowing rabi (winter) season crops in the High Barind Tract (HBT) in Bangladesh was by broadcasting seed followed by full tillage (Johansen et al. 2008a), with animal-drawn mould-board ploughs or more recently by rotary tillage with two-wheel tractors (2WT). The development of 2WT with planters attached (Hossain et al. 2009) has given rise to one-pass seeding, and the possibility of minimum tillage and conservation agriculture (Haque et al. 2004). Reduced and minimum tillage options are now being evaluated in the HBT for sowing of rabi season crops, including: strip tillage (ST; rotary blades only directly in front of seed delivering tines), zero tillage (ZT; seed delivering tines only), single pass shallow tillage (SPST; full rotary tillage preceding seed delivering tines), compared with conventional full tillage (power tiller cultivation, then broadcast seeding followed by another pass with the power tiller). These tillage types have been described in greater detail in Chapter 1.

The main advantages of minimum tillage techniques include: soil water conservation, targeted placement of seed and fertiliser, lower rates of fertiliser and seed, less labour and fuel required, and less time required to sow a crop (Baker and Saxton 2007; Haque et al. 2010). These benefits will likely lead to greater success in plant establishment and more land being sown to rabi season crops in the HBT.

Germination, emergence and early seedling growth of rabi season crops (such as chickpea and lentil) grown on residual soil moisture can be limited in the HBT soils due to rapid drying and hard-setting of the surface soil (Musa et al. 2001). One-pass seeding allows the time taken from rice harvest to sowing of the next crop to be minimized and increases the probability that the surface soil retains sufficient moisture for crop establishment (Kumar et al. 2007). Traditional methods of sowing rabi season crops could have two to five passes of tillage (Ali et al. 2007; Johansen et al. 2008a) lengthening the time taken to sow the crop and increasing drying of the surface soil due to disturbance of the soil structure which creates larger soil pores and voids (Rahmianna et al. 2000). Chapter 4 linked the soil physical requirements of chickpea
seeds for successful crop establishment to pot studies in Chapter 3. In this chapter the effects of different tillage types on the soil structure of the seed-bed are further investigated.

Different methods of tillage can affect crop establishment (Cook et al. 1995; Baker 2007b) and final seed yields (Horn et al. 1996; Barzegar et al. 2003; Kar and Kumar 2009). Soil water content, soil strength, aeration and temperature will be affected by tillage, but ideally these soil physical properties should not be limiting for crop establishment and early vigorous plant growth. The tillage method used, the soil type under cultivation, and the soil water content at cultivation will determine the resultant soil structure in which the seed is placed. In the case of minimum tillage techniques, the seed is row-sown and placed in a furrow and in the case of full tillage the seed, either broadcast or row-sown, is placed in a layer of fully cultivated soil. Successful germination and emergence of the seeds requires adequate seed-soil contact, appropriately sized aggregates and minimal soil compaction below and above the seed. Seed-soil contact controls the movement of water from the soil to the seed to allow the process of germination to begin. Water may also be available in the vapour phase and in some conditions the seed may imbibe water from the vapour phase to begin germination (Wuest et al. 1999; Wuest 2007). The size and distribution of aggregates controls the seed-soil contact and the proportion, size and continuity of voids within the seed-bed. Aggregate size can also limit seedling emergence as large clods can block the upward movement of seedlings (Nasr and Selles 1995; Dorsainvil et al. 2005). In the case of large aggregates and large voids, penetration of new roots can become limited due to buckling of the roots as they are less able to penetrate into the zones of high soil strength at the aggregate surface, even though the void itself is not limiting root growth (Braunack and Dexter 1989). Soil strength under the seed may be increased due to surface smearing of furrow surfaces, and above the seed through the use of a press wheel or roller. Where the previous crop was monsoon season rice, cultivation of the seed-bed for transplanting the rice can create a hard pan at 10-15 cm depth (Johansen et al. 2008b). High soil strength below the seed may limit root elongation and penetration into the seed-bed, limiting early seedling growth (Materechera et al. 1991; Nasr and Selles 1995).

Minimum tillage causes less disruption of the surface soil and retains crop residues on the soil surface, but reduces soil incorporation of organic matter. Over time, these changes in soil
and organic matter management have been found to improve soil structure, provide erosion control, and improve infiltration, aeration and drainage (Baker and Saxton 2007). Minimum tillage techniques have been found to increase soil organic matter content and improve plant available water and aggregate stability (Ellis et al. 1982; Barzegar et al. 2003; Bhattacharyya et al. 2006).

Bulk density has been found to decrease after tillage operations regardless of tillage type and number of passes (Ellis et al. 1982; Braunack and McPhee 1991; Barzegar et al. 2003). When measured directly after tillage occurs, the effect of tillage type on bulk density varies depending on number of passes, the use of compaction devices in the seed-bed such as press wheels or rollers and the initial soil water content (Ellis et al. 1982; Altikat and Celik 2011). Over multiple seasons, minimum tillage techniques have been found to have either higher bulk density, lower bulk density or no change when compared to full tillage (Lal et al. 1994; Bhattacharyya et al. 2006; Mupangwa et al. 2013). In some cases the use of minimum tillage has been found to improve profile soil water storage (Horn et al. 1996; Barzegar et al. 2003; Bhattacharyya et al. 2006) although minimum tillage may need to be implemented for a prolonged period for improvements to water storage to become evident (Licht and Al-Kaisi 2005).

The tillage type that achieves highest yields is not consistent; in some cases yields are greater with zero tillage (Hossain et al. 2009) while in other situations they are greater in minimum tillage over both conventional and zero tillage (Kar and Kumar 2009). Alternatively yields of crops sown with minimum tillage technology have been found to have no yield advantage compared to conventional tillage (Barzegar et al. 2003; Bhattacharyya et al. 2006).

Minimum tillage is still in the early stages of development in Bangladesh. Hence many questions have not been addressed. The suitability of different types of minimum tillage has not been well researched. Initial comparisons in 2007 (reported in Chapter 4) produced mixed results depending on the sowing date, but these results were obtained with an early version of minimum tillage planters for 2WT. In Bangladesh, relatively little crop residue is retained after harvesting T. Aman rice and the implications of relatively bare soil surface for the success of minimum tillage planting of rabi season crops have not been examined. Moreover, minimum
tillage is yet to be implemented across the whole crop sequence and so minimum tillage is being applied to establish crops in fields of the HBT that have been fully puddled then flooded for rice cultivation which creates a massive apedal condition into which chickpea are established. Finally, as discussed above in Chapter 4, chickpea establishment may be hindered due to the rapidly drying surface soil in the HBT and the access of chickpea to stored soil water during reproductive growth has a major influence on yield potential. Recognising these knowledge gaps, the objectives of this study were to:

1. evaluate the effect of the different minimum tillage techniques on seed-bed conditions and early chickpea establishment,
2. determine if tillage type influences final chickpea yields, and
3. determine the effect of tillage type on available water content and crop water use during the growing season.

5.2 Materials and methods

Three trials were sown in November during the rabi seasons of 2007-08, 2008-09 and 2009-10. From here on each trial will be referred to by the year of establishment rather than the year of harvest.

5.2.1 Weather

Daily temperature and rainfall data were collected by staff from the BRRI (Bangladesh Rice Research Institute) at Edulpur Village, Godagari Upazilla, Rajshahi Division. The weather station was approximately 10 km from the trial sites. Mean daily temperature was calculated as the average of the minimum and maximum daily temperatures.

5.2.2 2007 Tillage type and sowing date trial

In 2007, the trial investigated tillage type and sowing date. Details of this trial have been described in detail in Chapter 4. The trial had three levels of tillage (power tiller operated seeder (PTOS), strip tillage (ST) and zero tillage (ZT)) and four sowing dates. The trial was laid out as split plot design with sowing date as the main plot and tillage type as the sub plot. All details of plot design and crop management are in Table 4.1 in Chapter 4, and a description
of analyses completed in Chapter 4, Sections 4.2.1 to 4.2.3. For the purposes of comparison to the tillage techniques in 2008 and 2009, the PTOS was considered to create a similar seed-bed to the SPST. In both cases the seed-bed created was a shallow, fully tilled surface layer, of variable aggregate size. The main difference was that for PTOS in 2007 the seed and fertiliser were broadcast and for SPST in 2008 and 2009 the seed and fertiliser were both placed in rows through a furrow opener.

5.2.3 2008 Tillage type and residue trial

The trial was conducted in Kantopasha Village, Godagari Upazilla, Rajshahi Division, on a grey terrace soil (Aeric Haplaquept) which was representative of the region (Brammer 1996). The trial was laid out in a randomised complete block design with two factors. Factor one consisted of two residue treatments:

1. rice plants cut at 10 cm above ground and all rice residue immediately removed (Stubble = S); and
2. rice plants cut at 10 cm above ground and harvested rice residue laid on surface as a mulch (as currently done by farmers to dry crop before threshing) until chickpea sowing (Rice Retained = RR).

Factor two consisted of two sowing treatments:

1. strip tillage seeder (ST); and
2. single pass shallow tillage (SPST).

Due to an error in the allocation of treatments to plots, at sowing, there was an unequal replication (Figure 5.1). For each of residue treatment or sowing treatment there were ten replicates. However, for the combinations of RR+SPST and S+ST there were seven replicates and for S+SPST and RR+ST there were three.
Figure 5.1. Trial layout for the 2008 tillage type and residue trial.

A Chinese-made 2BG-6A planter was modified for each tillage treatment and attached to a two-wheel tractor (Dongfeng for ST or Sifeng for SPST). The SPST was sown with 48 rotary cutting blades arranged in front of the furrow openers, which was modified to deliver both the seed and fertiliser behind the rotary blade followed by a pressing roller. The ST comprised four rotary cutting blades arranged in front of each furrow opener, which again had been modified to deliver both the seed and fertiliser behind the rotary blades and was followed by a pressing roller. The furrow opening was made by a narrow leading edge tine.

Plots were 10 m long and 2.8 m wide with 8 rows at 40 cm spacing. At sowing (26 November 2008), primed (but without molybdenum or Rhizobium) chickpea (BARI Chola 5) seed was sown to have a 10 cm within-row spacing, at a rate of 40-45 kg of seed/ha. Triple superphosphate (TSP) was applied at a rate of 100 kg/ha, through the fertiliser box at sowing. Roundup® (Glyphosate 360 g/L) was sprayed on the 25 November 2008 at a rate of 250 ml/15 L H₂O. Follow-up hand weeding was done on 12 January and 10 February 2009. The crop was sprayed for pod-borer (Helicoverpa armigera) with Ripcord® (21.1 % Cypermethrin, 70.5 % Xylene) at a rate of 562 ml/ha on the 12 and 23 February and 2 March 2009.

5.2.3.1 Soil physical properties

Undisturbed soil cores were sampled at 10 cm increments to 40 cm depth in a soil pit within the experimental plot at sowing. Soil bulk density (ρb) was measured at each depth on two intact soil cores by the method of Cresswell and Hamilton (2002). Soil particle size analysis was measured on a surface sample (0 to 10 cm) collected from the site after harvest, this was a bulk sample also used in pot trial Experiments 3 and 4 in Chapter 3. The sample was bulked, air
dried and sieved to <2 mm before undergoing particle size analyses as described in Chapter 2, Section 2.2.3.

5.2.3.2 Soil water content

The previous rice crop was harvested on 18 November 2008. On this day the experimental plot design and the residue treatments were imposed and volumetric soil water contents ($\theta_{probe}$) were measured with a MP406 capacitance sensor (ICT International, Armidale NSW) at six random locations across the field at 10 cm increments to 40 cm. After implementation of the residue treatment (19 November 2008), $\theta_{probe}$ was measured daily until 4 December at the depths of 0-6 cm and 6-12 cm. Up until when the surface residue was removed from the RR treatment on 22 November 2008, $\theta_{probe}$ was also measured to 36 cm depth in the soil profile (6 cm increments to 36 cm).

Within the growing season, $\theta_{probe}$ in the soil profile was measured on three occasions: at sowing in 10 cm increments to 40 cm, at podding (30 January) in 10 cm increments to 60 cm, and at root sampling (23 February) at 15 cm increments to 60 cm. The calibration equation described in Chapter 4, Figure 4.1 was used to convert $\theta_{probe}$ to $\theta_v$ for each measurement. Where the MP406 was used to measure $\theta_v$, the depth reported was the depth in the profile at which the probe was inserted. Each measurement covered a depth of 6 cm, and where profile volumetric water content was calculated the 10 cm increment was used for the calculation. The assumption was that the soil directly below the probe was at a similar water content.

5.2.3.3 Crop growth observations

To determine the growth stages of the chickpea crop the dates recorded were: emergence, when 50 % of plants in a plot had flowered, when 50 % of plants in a plot had pods, and crop maturity. During crop growth the following measurements were taken: plant stand at emergence (four by 1 m row lengths in each plot), biomass at podding (quadrat, two rows by 1 m length in each plot), and biomass and grain yield at crop maturity (whole plot).

For final harvest of the whole plot, at physiological maturity plants were cut at ground level and biomass and yield data collected after air-drying. Pods were removed by traditional farmers’ method of threshing as described in Chapter 4, Section 4.2.2.
5.2.3.4 Root distribution

On 23 February 2009, the crop was sampled for root distribution. Five plots were selected from each of the tillage type treatments. Early crop growth in the SPST tillage treatment seemed to be more vigorous than in the strip tillage treatment. Therefore, chickpea root distribution was measured to determine if the vigorous shoot growth was related to increased root growth of chickpea plants sown into the SPST tillage treatment. Soil was sampled under representative sections of rows of chickpea plants. Shoots were excised from the surface and above-ground biomass determined. Blocks of soil 15 cm deep, 20 cm along the row and 10 cm across the row were sampled. Blocks were excavated using a spade. Four blocks per plot were sampled down the soil profile at 0-15, 15-30, 30-45 and 45-60 cm. Roots were separated from soil by washing. Extracted soil was placed with water in plastic buckets and left to soak for 1 to 3 hours. The slurry was washed through a 2 mm sieve and roots were collected by hand with the non-root material picked out or washed off. Root length was measured manually from the sum of lengths for each individual segment of root. Root volume was recorded by water displacement from a volumetric cylinder and root dry weights were recorded after oven drying at 65 °C to a constant weight. Root length density (RLD, root length/soil volume) and specific root length (SRL, root length/oven dry weight) were calculated for each sample.

5.2.3.5 Statistical analysis

Results were analysed using GenStat v11.1 (VSN International Ltd, United Kingdom). Due to the unequal replication the trial was analysed using linear mixed models (Residual maximum likelihood, REML). As REML was used the estimated means from the model and the average least significant differences (l.s.d.) were reported. An equal number of replications were sampled for root growth parameters, therefore analysis of variance (ANOVA) was used to analyse the data.
5.2.4 2009 Tillage type trial

The trial was conducted in the Choighati village, Godagari Upazilla, Rajshahi Division, from November 2009 to March 2010. It was conducted on grey terrace soil (Aeric Haplauquat) which was representative of the region (Brammer 1996) in a randomised block design with four replications. The trial had five tillage treatments using the Versatile Multi-crop Planter (VMP) attached to a Dongfeng type 2WT:

1. strip tillage (ST); four rotating blades in front of each furrow opener (narrow tines with a rounded leading edge) which delivered the seed and fertiliser followed by a pressing roller to cover and press soil around seed;
2. zero tillage (ZT); furrow opener only to create the furrow (narrow V-Shaped) where seed and fertiliser was placed, followed by a pressing roller to press soil around seed;
3. single pass shallow tillage (SPST), 32 rotating blades breaking the soil, followed by the furrow opener which delivered seed and fertiliser, followed by a pressing roller;
4. broadcast, a traditional 2WT with full rotary tillage was used to cultivate the soil once, followed by hand broadcast of seed and fertiliser, followed by another pass with the 2WT to incorporate the seed and fertiliser into the seed-bed; and
5. fallow plot, initial weed control by Roundup® (Glyphosate 360 g/L), sprayed on 24 November 2009, with no follow up weed control. No fertiliser applied.

In the ST, ZT, and SPST treatments, the fertiliser was delivered approximately 2 cm below the seed. Seeding depth varied with tillage type and was measured after sowing. Plot dimensions were 12.8 x 3.6 m, with 12 rows sown at 30 cm spacing in the ST, ZT and SPST treatments. Desi chickpea cv. Bari Chola 5 was sown at a rate of 45 kg/ha on the 25 November 2009. Triple superphosphate (TSP) was applied at sowing at a rate of 100 kg/ha. The TSP was drilled with the seed for the ST, ZT and SPST treatments. These rates of seed and fertiliser are based on the requirement of the broadcast treatment (Ali et al. 2007). Seed was primed with water for six hours, and drained for one hour prior to sowing. Roundup® (Glyphosate 360 g/L) was sprayed on all plots on 24 November 2009 at a rate of 250 ml/15 L H₂O. The crop was
sprayed for pod-borer with Ripcord® (21.1 % Cypermethrin, 70.5 % Xylene) at a rate of 562 ml/ha at 12 and 22 February 2009.

5.2.4.1 Soil physical properties

Soil samples were collected at sowing (25 November 2009) from four locations across the field at 10 cm increments to 60 cm depth. These samples were bulked, air dried and sieved to <2 mm. Soil particle size analysis was as described in Chapter 2, Section 2.2.3.2. Soil water potentials at -10 and -1500 kPa were measured using a pressure plate for duplicates of each soil sample as described by Cresswell (2002). Rings (3.5 mm diameter 3.8 mm high) filled with soil (approximately 25 g) were placed in a water bath and wet to saturation from below. After saturation, rings with soil were placed on a ceramic plate in the pressure chamber and the appropriate pressure applied. After equilibrium was reached, the soil was removed from the pressure chamber, weighed and oven-dried at 105 °C for 24 hours. Gravimetric water content ($\theta_g$) of the soil was then calculated. Volumetric water content ($\theta_v$) of the soil was then calculated from the gravimetric water content of the samples and the bulk density from the soils collected in the 2008 trial (Cresswell and Hamilton 2002).

Duplicate measurements of soil penetration resistance were taken from each plot at sowing with a field hand-held penetrometer (Eijkelkamp, the Netherlands). Measurements were taken from the depths 0-2.5, 2.5-5 and 5-10 cm. A cone with a 5 cm$^2$ base area was attached to the penetrometer shaft and pressed into the soil after which maximum resistance for each depth increment was recorded.

5.2.4.2 Soil water content

Volumetric soil water content ($\theta_{probe}$) was measured by the MP406 capacitance sensor (ICT International, Armidale NSW) during the chickpea growing season:

1. Before sowing from 20 to 24 November 2009 at the soil surface (0-6 cm) randomly across the trial site (n = 8).
2. At sowing on 25 November 2009. Sampled at two locations in each plot at two depths 0-6 and 6-12 cm. In addition, four soil profiles were measured to 60 cm in
10 cm increments. At each depth a soil sample was also taken for analysis of gravimetric soil water content ($\theta_g$).

3. After sowing at 0-6 and 6-12 cm depth on 2, 7, 10 and 18 December 2009.

4. At 50% podding (20 February 2010) and physiological maturity (21 March 2010). At one location in each plot, soil water was measured with the MP406 to 60 cm depth in 10 cm increments. Dry soil, deep in the profile prevented measurement to depth in some plots. At four locations, a soil sample was taken at each depth for gravimetric soil water analysis.

For each measurement with the MP406, an auger was used to dig to the desired depth and the probe inserted before a reading $\theta_{probe}$ was recorded. Three times during the season, gravimetric soil water contents ($\theta_g$) were also taken to a depth of 60 cm in 10 cm increments. Gravimetric soil water contents were converted to $\theta_v$ using bulk density from the 2008 trial as described in Section 5.2.3.1. (Cresswell and Hamilton 2002). These measurements provided a range of readings across the wet to dry range from which to calculate a site calibration curve. In this trial plot, 95 pairs of calculated volumetric water content ($\theta_v$) and volumetric soil water content ($\theta_{probe}$) were collected from the MP406 to create a calibration curve (Figure 5.2). The regression equation for the relationship was:

$$\theta_v = 0.8998(\theta_{probe}) - 4.2312 \quad r^2=0.7562.$$  

This relationship is valid for this 2009 trial site only. The equation used in the 2008 trial and presented in Chapter 4, was a combination of multiple trial sites with similar grey terrace soil types and was presented as a generic relationship to use for the grey terrace soil. For the 2009 site, a separate relationship was used because this site had 95 pairs of data.
5.2.4.3 Crop growth observations

Chickpea emergence was assessed four times from 8 to 23 days after sowing (DAS). At 11 DAS, depth of seed placement was measured. In each plot, two emerged seedlings had the soil around them removed until the seed was visible; the depth from the surface soil was then measured. The crop was monitored to determine when 50 % of plants in a plot had flowered, when 50 % of plants in a plot had pods and for chickpea maturity. At 50 % podding and at crop maturity, quadrats were sampled in each plot. The quadrats were 1 m long and three rows wide in the ST, ZT and SPST treatments, and 1 m² in the broadcast treatment. At podding, one quadrat was sampled per plot and at harvest two quadrats were sampled per plot. Plant growth parameters recorded for each quadrat where appropriate were: plant numbers, fresh and dry biomass (g), seed weight (g), pod numbers, pod fresh and dry weight (g), number of unfilled pods, 100 seed weight (g), and number of seeds in 10 pods. At harvest, all rows of each plot were sampled for measurements of grain yield (kg/ha) and total above-ground biomass (kg/ha). At physiological maturity the plants were cut at ground level and biomass yield data collected after air-drying. Pods were removed by traditional farmers’ method of threshing as described in Chapter 4, Section 4.2.2.
5.2.4.4 Statistical analysis

Analysis of variance (ANOVA) was used to test the effects of treatments using GenStat v11.1 (VSN International Ltd, United Kingdom). The means, standard error of the means and the least significant differences (I.s.d.) were reported as necessary.

5.3 Results

5.3.1 Weather

Details of daily minimum and maximum temperatures and rainfall are shown in Chapter 4, Figure 4.2. The dates of phenological development for the tillage type trials in 2008 and 2009 are designated in the figures by TT2008 and TT2009. In 2007 and 2008 within-season rainfall was 10.2 and 31.2 mm, respectively; in 2009 there was no within-season rainfall.

5.3.2 Soil physical properties

The soil physical properties from the trials established in 2008 and 2009 are shown in Table 5.1. The surface soil texture is classified as a silt loam (McDonald et al. 1998). For soils in the HBT region, the values of $\theta_v$ at field capacity and wilting point reported in this work are similar to those reported in Ali (2000), and similar to the $\theta_v$ at wilting point determined in Idris and Munirul Huq (1987). In Idris and Munirul Huq (1987), the $\theta_v$ at field capacity was lower (36 % vs >47 %) for a silt loam texture class soil than the value in the present study. For the values of field capacity, it must be noted that disturbed soil samples (<2 mm sieved) were analysed in the present study. The bulk density values from 2008 were used to convert the $\theta_s$ to $\theta_v$ at field capacity and wilting point for the 2009 samples.
Table 5.1. Soil physical properties of the trial sites established in 2008 and 2009 in the High Barind Tract of Bangladesh.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Bulk density (g/cm³)</th>
<th>Volumetric water content (θv) at -10 kPa (%)</th>
<th>Volumetric water content (θv) at -1500 kPa (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2008 Tillage type and mulch trial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10</td>
<td>50</td>
<td>28</td>
<td>22</td>
<td>1.3</td>
<td>47.1</td>
<td>15.0</td>
</tr>
<tr>
<td>10-20</td>
<td></td>
<td></td>
<td></td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-30</td>
<td></td>
<td></td>
<td></td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30-40</td>
<td></td>
<td></td>
<td></td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40-50</td>
<td></td>
<td></td>
<td></td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2009 Tillage type trial</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10</td>
<td>50</td>
<td>26</td>
<td>24</td>
<td></td>
<td>48.7</td>
<td>15.1</td>
</tr>
<tr>
<td>10-20</td>
<td>48</td>
<td>29</td>
<td>23</td>
<td></td>
<td>51.5</td>
<td>13.4</td>
</tr>
<tr>
<td>20-30</td>
<td>43</td>
<td>29</td>
<td>29</td>
<td></td>
<td>47.8</td>
<td>15.7</td>
</tr>
<tr>
<td>30-40</td>
<td>47</td>
<td>30</td>
<td>23</td>
<td></td>
<td>54.8</td>
<td>17.6</td>
</tr>
<tr>
<td>40-50</td>
<td>53</td>
<td>28</td>
<td>18</td>
<td></td>
<td>49.8</td>
<td>15.4</td>
</tr>
<tr>
<td>50-60</td>
<td>49</td>
<td>25</td>
<td>27</td>
<td></td>
<td>50.8</td>
<td>20.3</td>
</tr>
</tbody>
</table>

5.3.3 2007 Tillage type and time of sowing trial

5.3.3.1 Tillage method

At sowing of the 2007 trial, the machine operator and participating scientists made observations regarding the ease of cultivation and resultant seed-bed conditions of each tillage type. These observations are compiled in Table 5.2 and relate to observations of soil conditions after sowing under high soil water conditions.

5.3.3.2 Soil water content

The results of the analysis of soil water content in the 2007 time of sowing trial are discussed in Chapter 4, Section 4.3.2. Figure 4.4 shows the soil water content and soil strength in the surface soil over the period of sowing until after emergence. Figure 4.10 shows the soil water contents with depth (70 cm) for each sowing date, at 50 % flowering and physiological maturity.
Table 5.2. Observations of soil conditions at sowing of the 2007 trial with the tillage treatments of the power tiller operated seeder (PTOS), strip tillage (ST) and zero tillage (ZT). The treatments have been ranked where one is optimal for sowing and seed-bed preparation and three is poor.

<table>
<thead>
<tr>
<th></th>
<th>Power tiller operated seeder</th>
<th>Tillage type</th>
<th>Zero tillage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of sowing at high soil water content</td>
<td>Easiest</td>
<td>1</td>
<td>Most difficult</td>
</tr>
<tr>
<td>Seed dropping</td>
<td>Less gap between seeds</td>
<td>Less gap between seeds</td>
<td>More gap between seeds</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Tillage depth</td>
<td>Shallower</td>
<td>Deeper</td>
<td>Deeper</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Tillage quality</td>
<td>Better at high θυ</td>
<td>Smearing formed along furrow wall</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Surface soil water conservation</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Emergence success</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

5.3.3.3 Chickpea growth and yield

The data for chickpea emergence for the 2007 time of sowing trial are presented in Chapter 4, Section 4.3.3. Figure 4.11 shows the PPD of the crop for each treatment at emergence and harvest. The details of crop growth and yield for the 2007 time of sowing trial are discussed in Chapter 4, Section 4.3.4. Table 4.3 provides all details of crop phenological development, whilst Figures 4.12 to 4.15 show plant biomass, pod numbers and final grain yield.

5.3.4 2008 Tillage type and residue trial

5.3.4.1 Tillage method

The two different tillage methods provided very different seed-beds for the chickpea plants. As in the description of tillage methods in the 2007 trial, the observations relate to soil conditions after sowing under high soil water content. The SPST cultivated the entire soil surface and covered the seed with an even covering of various-sized aggregates of soil (Figure 5.3a and b). The ST only cultivated the soil within the seed furrow and soil did not cover the seed uniformly in the row (Figure 5.4a and b). Much of the furrow was left with seed
uncovered as the press wheel was ineffective. There was evidence of the furrow wall being smeared during the sowing process (Figure 5.4c).

Figure 5.3. The surface conditions of soil after sowing of the 2008 tillage type trial with single pass shallow tillage (SPST) in a) wide shot where yellow lines indicate the boundary of three rows sown after one-pass and b) close-up of the seed row.
Figure 5.4. The surface conditions of soil after sowing of the 2008 tillage type trial with strip tillage (ST) in a) wide shot, b) close-up of the seed row and c) close-up of the smeared furrow wall and chickpea seed.
5.3.4.2 Soil water content

The pattern of soil drying at 0-6 cm and 6-12 cm from harvest of the previous rice crop to 8 DAS are shown for each residue treatment (Figure 5.5) or tillage treatment (Figure 5.6). The RR treatment had higher surface $\theta_v$ (0-6 cm) for 13 of the 14 dates where a measurement was taken. The exception was 24 November, which was the first reading taken, one day after the surface mulch was removed (Figure 5.5). However, only on 21 November was the RR treatment significantly greater in $\theta_v$ at 31.8 % compared with 29.6 % in the S treatment ($P <0.05$). At the 6-12 cm depth, there was no effect of mulch treatment. After implementation of the tillage treatment, $\theta_v$ continued to decrease but was not different between tillage treatments at either depth (Figure 5.6). When the depths 10-35 cm were monitored, no differences of $\theta_v$ were seen between residue treatments over time (data not shown).

![Figure 5.5](image.png)

**Figure 5.5.** Soil water content ($\theta_v$) (%) at 0-6 cm and 6-12 cm depth for the surface residue treatments of rice retained (RR) and standing stubble (S) in the 2008 trial (residue treatments $n=10$, at rice harvest $n=6$). Error bars were ±1 standard error of the mean and * indicates significant difference at $P = 0.05$ level between treatments on that date of measurement.
Figure 5.6. Soil water content ($\theta_v$) (%) at 0-6 cm and 6-12 cm depth for the tillage treatments of strip tillage (ST) and single pass shallow tillage (SPST) (Tillage treatment n =10). Error bars were ± 1 standard error of the mean.

The chickpea crop was sown (26 November) at $\theta_v$ of 29.4 and 28.1 % at 0-6 cm depth in the RR and S treatments, respectively. After sowing, the plots which had the RR treatment continued to have the higher mean surface $\theta_v$ for most days, but significant differences were only found on the 1 December ($P<0.05$) (Figures 5.5 and 5.7). No real trend can be discerned for $\theta_v$ between the SPST or ST tillage methods used to sow the crop at this depth (Figure 5.7). Overall the surface $\theta_v$ continued to decrease with days after sowing.
5.3.4.3 Chickpea growth and yield

The growth stages of the 2008 chickpea crop are presented in Table 5.3. During crop growth, 26 November 2008 to 30 March 2009, 31.2 mm of rainfall was recorded, albeit at the nearest weather station 10 km from the trial location. There were no apparent constraints due to disease (BGM, collar rot, wilt), insect (pod-borer) or weeds in this trial, due to effective control measures as described in Section 5.2.3.

Table 5.3. Phenology of crop development of the chickpea in the 2008 tillage type and mulch trial in Rajshahi, Bangladesh.

<table>
<thead>
<tr>
<th>Plant phenology</th>
<th>Date</th>
<th>Days after sowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sowing date</td>
<td>26 November 2008</td>
<td></td>
</tr>
<tr>
<td>Emergence date</td>
<td>5 December 2009</td>
<td>9</td>
</tr>
<tr>
<td>50 % flowering</td>
<td>20 January 2009</td>
<td>55</td>
</tr>
<tr>
<td>50 % podding</td>
<td>30 January 2009</td>
<td>65</td>
</tr>
<tr>
<td>Crop physiological maturity</td>
<td>25 March 2009</td>
<td>119</td>
</tr>
<tr>
<td>Crop harvest</td>
<td>30 March 2009</td>
<td>124</td>
</tr>
</tbody>
</table>
Mean emergence of the plots sown with the SPST was 66.6 plants/m$^2$, compared with 40.1 plants/m$^2$ for those plots sown with ST ($P<0.001$) (Table 5.4). Observation of the plots indicated that the emerged plants had more vigorous growth as well as greater number of plants emerged in the SPST than in the ST. The interaction of residue treatment with tillage was significant, since the ST with the RR as mulch did have a significantly greater emergence than the S treatment, while the SPST had greater emergence in the S treatment (Table 5.4).

Chickpea grain yield and biomass were not significantly different between residue treatments. However, biomass parameters throughout the season and grain yield were significantly greater in the SPST treatment in comparison to the ST (Table 5.4 and Table 5.5).
Table 5.4. Crop growth parameters from the 2008 chickpea tillage type and surface residue trial. Tillage types were single pass shallow tillage (SPST) and strip tillage (ST). Residue treatments were cut rice retained (RR) on the surface as mulch and standing stubble (S). The mean of plant population after emergence (plant/m²) and dry biomass (kg/ha) on 30 January (at 50 % podding), and 23 February (root sampling) are presented.

### Plant population after emergence (plant/m²)

<table>
<thead>
<tr>
<th>Tillage Treatment</th>
<th>Residue Treatment</th>
<th>RR</th>
<th>S</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPST</td>
<td></td>
<td>63.2</td>
<td>70</td>
<td>66.6</td>
</tr>
<tr>
<td>ST</td>
<td></td>
<td>45.8</td>
<td>34.4</td>
<td>40.1</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>54.5</td>
<td>52.2</td>
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Significance¹

<table>
<thead>
<tr>
<th>Tillage</th>
<th>P-value</th>
<th>L.s.d. (P = 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>&lt;0.001</td>
<td>5.8</td>
</tr>
<tr>
<td>Mulch</td>
<td>n.s.²</td>
<td></td>
</tr>
<tr>
<td>Tillage x Mulch</td>
<td>&lt;0.01</td>
<td>6.3-9.7</td>
</tr>
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</table>

### Biomass at podding (kg/ha)

<table>
<thead>
<tr>
<th>Tillage Treatment</th>
<th>Residue Treatment</th>
<th>RR</th>
<th>S</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPST</td>
<td></td>
<td>1065</td>
<td>994</td>
<td>1029</td>
</tr>
<tr>
<td>ST</td>
<td></td>
<td>679</td>
<td>518</td>
<td>599</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>872</td>
<td>756</td>
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</table>

Significance

<table>
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<th>P-value</th>
<th>L.s.d. (P = 0.05)</th>
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</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>Mulch</td>
<td>n.s.</td>
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</tr>
<tr>
<td>Tillage x Mulch</td>
<td>n.s.</td>
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</tr>
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</table>

### Biomass at root sampling (kg/ha)

<table>
<thead>
<tr>
<th>Tillage Treatment</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPST</td>
<td>1707</td>
</tr>
<tr>
<td>ST</td>
<td>703</td>
</tr>
</tbody>
</table>

Significance

<table>
<thead>
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<th>Tillage</th>
<th>P-value</th>
<th>L.s.d. (P = 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>&lt;0.001</td>
<td>416</td>
</tr>
</tbody>
</table>

¹The level of significance and least significant difference (L.s.d) at the 5% level are reported for the comparable means of (i) the interaction between tillage and residue treatments, (ii) the main effect of tillage treatment, and (iii) the main effect of residue treatment.
²n.s. = not significant
Table 5.5. The yield parameters from the 2008 chickpea tillage type and surface residue trial. Tillage types were single pass shallow tillage (SPST) and strip tillage (ST). Residue treatments were cut rice retained (RR) on the surface as mulch and standing stubble (S).

<table>
<thead>
<tr>
<th>Grain yield (kg/ha)</th>
<th>Tillage Treatment</th>
<th>Residue Treatment</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPST</td>
<td>RR 576</td>
<td>559</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S 543</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>RR 299</td>
<td>228</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S 157</td>
<td></td>
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<td></td>
<td>Mean</td>
<td>RR 437</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S 350</td>
<td></td>
</tr>
</tbody>
</table>

Significance\(^1\)  
- **P-value**  
  - Tillage: \(<0.001\)  
  - Mulch: n.s.\(^2\)  
  - Tillage x Mulch: n.s.

<table>
<thead>
<tr>
<th>Final harvest biomass (kg/ha)</th>
<th>Tillage Treatment</th>
<th>Residue Treatment</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPST</td>
<td>RR 1103</td>
<td>1076</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S 1050</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>RR 614</td>
<td>486</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S 357</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>RR 858</td>
<td>703</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S 703</td>
<td></td>
</tr>
</tbody>
</table>

Significance  
- **P-value**  
  - Tillage: \(<0.001\)  
  - Mulch: n.s.  
  - Tillage x Mulch: n.s.

<table>
<thead>
<tr>
<th>Harvest index</th>
<th>Tillage Treatment</th>
<th>Residue Treatment</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPST</td>
<td>RR 0.51</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S 0.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>RR 0.49</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S 0.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>RR 0.50</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Significance  
- **P-value**  
  - Tillage: n.s.  
  - Mulch: n.s.  
  - Tillage x Mulch: n.s.

\(^1\)The level of significance and least significant difference (l.s.d) at the 5 \(\%\) level are reported for the comparable means of (i) the interaction between tillage and residue treatments, (ii) the main effect of tillage treatment, and (iii) the main effect of residue treatment.

\(^2\)n.s. = not significant
5.3.4.4 Root distribution

There was no significant difference in root length and RLD between tillage treatments or with depth (Figure 5.8 and Figure 5.9). The root length was 56 m and RLD was 1.8 cm/cm³. With each tillage type this parameter showed no trend with depth, other than a minor decrease at the 45-60 cm depth. Across both tillage treatments, the root volume did decrease with depth ($P < 0.01$) (Figure 5.9). The root volume at the 0-45 cm depths were significantly greater than the 45-60 cm depths ($P < 0.01$).

Root weight decreased ($P < 0.001$) with soil depth across both tillage treatments. Across the two tillage treatments, the root biomass of the surface (0-15 cm) was significantly higher than all other depths. At a depth of 0-15 cm, the SPST root biomass was significantly higher than ST and root biomass decreased with soil depth ($P < 0.05$) (Figure 5.8).

Specific root length increased with soil depth ($P < 0.001$) (Figure 5.8). Across the depth increments, the SRL of tillage treatments significantly increased below 30 cm soil depth. In the SPST, there was significant difference between the SRL in the 0-30 cm soil profile and the SRL of the deeper soil profile (>30 cm). Whilst in the case of the ST there was a significant difference between the 0-30 cm depths and the 30-45 cm depth, but not the 45-60 cm depth.

A low SRL indicates that, for the same length of root, the root weight is greater than for a sample with a high SRL. This may indicate that at 0-15 cm in the SPST, the plant roots were thicker than the ST. The fact that root length did not alter with soil depth, while root weight decreased indicated that at shallower depths the roots had become thicker, while at depth the roots were thinner, which was reflected in the SRL.
Figure 5.8. The mean of a) specific root length (SRL) (m/g), b) root dry weight (g) and c) root length (m), for the single pass shallow tillage (SPST) and strip tillage (ST) treatments at the soil depths 0-15, 15-30, 30-45 and 45-60 cm. Error bars indicate 1 standard error of the mean (n =5). Means with identical letters are not significantly different.
Figure 5.9. The mean of a) root volume (cm$^3$) and b) root length density (RLD) (cm/cm$^3$) for the single pass shallow tillage (SPST) and strip tillage (ST) treatments at the soil depths 0-15, 15-30, 30-45 and 45-60 cm. Error bars indicate 1 standard error of the mean (n =5). Means with identical letters are not significantly different for the factor of depth only.

5.3.4.5 Profile soil water content

Soil profile water content three days before sowing (23 November) amounted to 95 mm water in the top 40 cm of the soil profile (Error! Reference source not found.). On 30 January and 23 February, this had dropped to 61 mm in 60 cm of soil. The only rainfall between these measurements was on 11 February which may account for the refilling of the surface of the profile to 15 cm depth in both the tillage treatments. There was no difference in $\theta_v$ between tillage types at any depth at either time of measurement. From 30 January to 23 February, there was a decrease in the $\theta_v$ at the 45-60 cm depth by 5.5 % ($P <0.01$) (Error! Reference source not found.). This may indicate that during this period roots have grown to the 60 cm depth and used available soil water.
Figure 5.10. The mean volumetric soil water content ($\theta_v$) (%) to 60 cm depth in the soil profile during the tillage trial of 2008. Tillage treatments were single pass shallow tillage (SPST) and strip tillage (ST). Measurements were taken at sowing (26 November 2008), puddling (30 January 2009) and when plant roots were sampled (23 February 2009). Error bars indicate ± 1 standard error of the mean.

5.3.5 2009 Tillage type trial

5.3.5.1 Soil conditions at sowing

At sowing, the water content was slightly wetter than judged to be optimum. The furrow was prone to surface smearing in the ST and ZT. For the row-sowing tillage types, the operator had to take care to ensure the furrow opener did not become blocked by soil preventing the drop of seed and fertiliser. In addition, the operator also had to ensure the roller used as the final covering and pressing tool did not have a layer of soil build up on its surface. Figure 5.11a shows the power tiller used to cultivate the soil for the broadcast tillage treatment. Figure 5.11b shows the set up of the VMP with rotary blades in front of furrow openers which deliver the seed and fertiliser (roller not shown). The structure of the surface soil in the seed-beds is shown in Figure 5.11c for SPST and in Figure 5.11d for ST.

a)  

b)
Figure 5.11. Pictures of a) the power tiller used to incorporate the broadcast chickpea seed, b) the Versatile Multi-crop Planter (VMP) with rotary blades in front of furrow openers for seed and fertiliser placement (roller not shown) and the soil structure in the seed-bed for c) single pass shallow tillage (SPST) and d) strip tillage (ST).

At sowing, the soil strength was 0.45 MPa in the 0-2.5 cm surface soil layer which was significantly \( P < 0.001 \) less than the 0.57 MPa measured in the 2.5-10 cm layer. When the previous rice crop was awaiting harvest, the \( \theta_v \) of the 0-6 cm surface soil across the trial area was 29.4 ± 0.42 %, and by sowing the \( \theta_v \) of the surface soil was 26.1 ± 0.32 % (Figure 5.12). Across all treatments, the \( \theta_v \) of the surface soil in the seed row decreased from sowing until the 18 December (23 DAS), when no further measurements were taken. The fallow treatment and ZT treatment lost the most \( \theta_v \) over this time equivalent to 8.4 and 8.9 %, respectively. The broadcast treatment seemed to have the least variation in \( \theta_v \) over the measurement period and the least overall loss of water (3.3 %).

From the 2 to 18 December, the fallow treatment always had less soil water in the 0 to 6 cm layer of soil than the broadcast, SPST and ST treatments \( P < 0.05 \). During this period, the ZT
treatment was significantly lower than the other tillage treatments; however this was not consistent across all the treatments or dates of measurement. The heavy fog before 10 December was associated with an increase in \( \theta_v \) in all treatments except the fallow treatment.

The \( \theta_v \) of the layer of soil from 6-12 cm in the seed row of the tillage treatments and fallow treatment were not different at any time during chickpea emergence (Figure 5.12). The \( \theta_v \) of all treatments across all dates of the 0-6 cm layer was less than the \( \theta_v \) of the 6-12 cm layer. The fog events before the 10 December measurement may also have resulted in a slight increase in the \( \theta_v \) of the 6-12 cm layer of all treatments.

**Figure 5.12.** The mean volumetric soil water content (\( \theta_v \)) (%) measured during the period from rice harvest to chickpea sowing and emergence, 20 November to 18 December 2009. The soil depths measured were a) 0-6 cm and b) 6-12 cm. Treatments were the tillage types: broadcast (▲), single pass shallow tillage (SPST; ●), zero tillage (ZT; ♦), strip tillage (ST; ■), and an unsown fallow treatment (△). In figure a) pre-sowing measurements (○) of \( \theta_v \) are shown with standard error bars. For the tillage and fallow treatments floating error bars for each date of measurement indicate the least significant difference (l.s.d.) at \( P = 0.05 \).
5.3.5.2 Chickpea growth and yield

The growth stages of the chickpea crop are presented in Table 5.6, representing the time taken to reach the key crop development phases of 50 % flowering, 50 % podding and physiological maturity which varied by no more than 3 days among tillage types. During crop growth, no rainfall was recorded at the site. Intermittent heavy fog did occur during the early growth period from sowing until 10 December. There were no apparent constraints due to disease (BGM, collar rot, wilt), insect (pod-borer) or weeds in this trial, due to effective control measures as described in Section 5.2.4.

Table 5.6. Phenology of chickpea development of the chickpea in the 2009 tillage type trial in Rajshahi, Bangladesh.

<table>
<thead>
<tr>
<th>Plant phenology</th>
<th>Date</th>
<th>Days after sowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sowing date</td>
<td>25 November 2009</td>
<td></td>
</tr>
<tr>
<td>Emergence date</td>
<td>2 December 2010</td>
<td>7</td>
</tr>
<tr>
<td>50 % flowering</td>
<td>6 to 7 February 2010</td>
<td>73-74</td>
</tr>
<tr>
<td>50 % podding</td>
<td>12 to 14 February 2010</td>
<td>80-81</td>
</tr>
<tr>
<td>Crop physiological maturity</td>
<td>22 to 24 March 2010</td>
<td>117-119</td>
</tr>
<tr>
<td>Crop harvest</td>
<td>At physiological maturity</td>
<td></td>
</tr>
</tbody>
</table>

The ST treatment had the greatest emergence, reaching 70 plants/m² at 8 DAS in comparison to less than 60 plants/m² for all other treatments (Figure 5.13). By 12 DAS, the emergence of the ZT treatment had improved so that it reached a similar emergence count to the ST treatment. In comparison the SPST treatment had a static rate of emergence from 8 to 12 DAS with a slight increase to 23 DAS, the final count of emergence. The broadcast treatments had no real change in total emerged plants from 8 to 23 DAS. The final emergence counts at 23 DAS were significantly lower in the broadcast tillage treatment (at 24 plants/m²) compared to the other tillage treatments (plant numbers between 68 to 81 plants/m²) \( (P <0.001) \) (Figure 5.13). Mean seed depth was 2.5 cm in the SPST, significantly shallower than the other tillage treatments that had seed depths of 3.5 to 4.2 cm \( (P <0.01) \).

The plant sampling at 89 DAS (22 February) was after 50 % podding was recorded. Chickpea growth parameters comprising plant numbers \( (P <0.001) \) (Figure 5.13), stem and leaf dry biomass \( (P <0.05) \), pod numbers \( (P <0.05) \) and pod fresh weight were all less in the
broadcast tillage treatment than all other tillage types (Figure 5.14). The plant count, pod numbers and pod fresh weights in the broadcast tillage treatment had mean values less than 50% that of the other treatments. The stem and leaf dry biomass of the broadcast treatment was 70% of the values of the other tillage treatments. At this sampling time, the SPST treatment also had slightly fewer plant numbers than the ST treatment ($P <0.001$). However, by crop maturity only plant numbers of the broadcast tillage treatment were less than the other tillage treatments ($P <0.001$) (Figure 5.13).

![Figure 5.13. The mean chickpea plant numbers (plants/m$^2$) at emergence, podding and harvest for the tillage type trials sown in 2009. From 3 to 23 DAS, plant numbers relate to emergence. Treatments were the tillage types: broadcast (▲), single pass shallow tillage (SPST; ●), zero tillage (ZT; ♦), and strip tillage (ST; ■). Error bars indicate the least significant difference (l.s.d.) at $P =0.05$.](image_url)
Figure 5.14. The mean of chickpea growth parameters of fresh pod weight (g/m²), pod number (pods/m²), and leaf and stem dry biomass (g/m²), at podding (89 days after sowing (DAS), 22 February 2010) and physiological maturity (117 DAS, 22 March 2010) for the tillage type trial sown in 2009. Treatments were the tillage types: broadcast, single pass shallow tillage (SPST), zero tillage (ZT), and strip tillage (ST). Error bars indicate the least significant difference (l.s.d.) at $P=0.05$.

At crop maturity (117 to 120 DAS), the whole plot harvest of chickpea biomass ($P<0.05$) and grain ($P<0.05$) was significantly less in the broadcast tillage treatment than the ZT and SPST treatments (Figure 5.15). The ZT treatment had the highest mean biomass and grain yields at 3153 and 1817 kg/ha, respectively.
Figure 5.15. The mean of chickpea final grain yield (kg/ha) (black bar) and above-ground biomass (kg/ha) (grain + stem + leaf) (open bar) (119 DAS, 24 March 2010) for the tillage type trial sown in 2009. Treatments were the tillage types: broadcast, single pass shallow tillage (SPST), zero tillage (ZT), and strip tillage (ST). Error bars indicate the least significant difference (l.s.d.) at $P = 0.05$.

Analysis of the quadrats sampled at final harvest showed no significant differences among any treatment for dry biomass, grain weight, pod weight, total pod number, seeds in 10 pods or weight of 100 seeds. Table 5.7 reports the results of the mean dry weight of the plant biomass, grain weight and pod numbers sampled in quadrats. Across all treatments the mean of unfilled pods was equivalent to 13 % of the total number of pods and the mean number of seeds in 10 pods was $14.6 \pm 0.49$. Plant count was again significantly less in the broadcast tillage treatment than the other tillage treatments at 38 plants/m$^2$ in comparison to 60 to 66 plants/m$^2$ in the other treatments (Figure 5.13) ($P < 0.001$).
Table 5.7. The mean above-ground biomass (g/m²), grain yield (g/m²), and pod number (pods/m²), of the chickpea plants sampled from quadrats at harvest (119 DAS, 24 March 2010) for the tillage type trial sown in 2009. Treatments were the tillage types: broadcast, single pass shallow tillage (SPST), zero tillage (ZT), and strip tillage (ST).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Biomass (g/m²)</th>
<th>Grain yield (g/m²)</th>
<th>Pod number (pods/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcast</td>
<td>334</td>
<td>151</td>
<td>1268</td>
</tr>
<tr>
<td>SPST</td>
<td>353</td>
<td>168</td>
<td>1422</td>
</tr>
<tr>
<td>Strip</td>
<td>362</td>
<td>182</td>
<td>1436</td>
</tr>
<tr>
<td>Zero</td>
<td>374</td>
<td>182</td>
<td>1574</td>
</tr>
</tbody>
</table>

l.s.d. at P = 0.05 n.s. 1 n.s. n.s.

P -value 0.499 0.554 0.352

1n.s. = not significant

5.3.5.3 Soil water content

Soil water content ($\theta_v$) was measured to depth on three occasions during the chickpea crop growth before sowing, at podding and maturity. There was significant loss of $\theta_v$ from the soil profile across all tillage treatments from sowing to podding (Figure 5.16). The extraction of $\theta_v$ in the fallow treatment was limited to the surface 20 cm, whilst in the tillage treatments $\theta_v$ was extracted to depths between 60 and 80 cm. From podding to harvest there was little change in the $\theta_v$ at each depth increment to 40 cm for sown plots, however in the fallow treatment during this period losses of $\theta_v$ did occur in the 20-40 cm layer of the profile. At all depths below the surface, the fallow treatment was significantly greater in $\theta_v$ at podding ($P <0.05$) compared to the tillage treatments, whilst the broadcast treatment was not different to the fallow treatment at depths of 60 cm and below.

The $\theta_v$ measurements taken to depth at sowing, podding and physiological maturity were used to calculate profile soil water content (SWC). Depth of sampling at these three times varied depending on the ease of sampling at depth in the drying profile. The profile SWC in 60 cm of soil was 126 mm at sowing (n =2), declining to 57.4 ± 5.3 mm at podding (89 DAS, n=20). From podding to harvest the profile SWC in 50 cm of soil decreased from 45.3 ± 4.2 to 37.2 ± 2.4 mm, a minimal decrease suggesting that in the top 50 cm of soil the chickpea crop had extracted most available water by podding. The initial drop in profile SWC indicates that from sowing to harvest approximately 69 mm of water was used as evapotranspiration in the
surface 50 cm. For the purpose of comparison between treatments and measurement times in Figure 5.17 the depth of calculation of the profile SWC was limited to 50 cm. At the period of chickpea podding, the fallow treatment had a profile SWC of 77.4 mm which was significantly greater than all tillage treatments (P <0.001). By chickpea harvest, the profile SWC of the fallow treatment was 47.7 mm, indicating that there was significant depletion of profile SWC in these plots. The fallow treatment still had profile SWC significantly greater than the ST, ZT and SPST plots at harvest (P <0.05).
Figure 5.16. The mean volumetric soil water content ($\theta_v$) (%) at 10 cm increments down the soil profile in the tillage and fallow treatments. Tillage treatments were the tillage types: broadcast, single pass shallow tillage (SPST), zero tillage (ZT), and strip tillage (ST). Measurements were taken at sowing (▼, 25 November 2009), podding (●, 20 February 2010) and crop maturity (○, 21 March 2010). Error bars indicate ± 1 standard error of the mean.
Figure 5.17. The mean profile soil water content (SWC) (mm) to 40 cm at sowing (grey bar), podding (filled bars) and harvest (unfilled bars) for the tillage type trial sown in 2009. Treatments were the fallow and the tillage types: broadcast, single pass shallow tillage (SPST), zero tillage (ZT), and strip tillage (ST). Error bars indicate the least significant difference (l.s.d.) at $P = 0.05$ between the tillage and fallow treatments within each measurement period of either podding or harvest.
5.4 Discussion

In Chapters 3 and 4, it was determined that the change from broadcast to mechanised row-sowing in the HBT of Bangladesh allows timely sowing into soil physical conditions (soil water, soil strength) which do not limit the success of chickpea crop establishment. Optimum soil physical conditions are more likely to occur with mechanised row-sowing in comparison with the traditional broadcast method of sowing. In this chapter the different methods of mechanised row-sowing, from full tillage to zero tillage were investigated to determine if any one type of tillage was better suited to conditions required for chickpea crop establishment in the HBT of Bangladesh, and if tillage type influenced final grain yields.

5.4.1 Seed-bed conditions

In this work, the furrow opener was the same shape for all mechanised sowing operations. The number and configurations of rotary blades in front of the furrow opener controlled the shape and size of the resulting furrow. Whether the shape of the furrow is U-shape or V-shape will control the loss of vapour from the furrow (Baker 2007b). The furrow shape in ZT was more of a V-shape as there were no rotary blades, whereas the rotary blades in the ST create more of a U-shaped furrow: in SPST the furrow was less defined and with broadcast there was no furrow, but a loose layer of soil within which the seed was sown. With ZT, the V-shaped nature of the furrow and the poor soil covering can restrict the seed-soil contact to only the furrow wall. In addition, a V-shaped furrow is prone to greater vapour loss and there are greater zones of soil compaction than a U-shaped furrow (Baker 2007b). In theory, U-shaped furrows allow greater seed-soil contact with the furrow floor and walls. A greater area of seed in contact with the soil can improve the uptake of water from the soil to the seed and improve germination success (Rahmianna et al. 2000), although at high soil water contents soybean (Glycine max L. Merr.) and mungbean seedlings have been found to establish when they remain uncovered after sowing (dibbling technique) (Rahmianna et al. 2000). Vapour loss has been a problem associated with dry soil (Baker 2007b), and layers of compaction around the furrow walls are associated with wet soils (Baker 2007d, 2007b).
General descriptions of tillage types and seed-bed characteristics after sowing from observations of the 2007 to 2009 tillage type trials are:

- Incorporation of broadcast with power tillage results in seed being placed at variable depths, soil aggregate size tends to span a greater range and include a greater proportion of larger aggregates which can limit seed coverage and seed-soil contact.
- Single pass shallow tillage has benefits which include, ease of cultivation by the machine, better seed fall into the furrow and better soil tilth but shallower seed depth which may be detrimental.
- Strip tillage had similar benefits to SPST, but the soil tilth in the furrow was not as fine in aggregate size as in the SPST and seed depth was likely to be deeper but more uniform.
- Zero tillage was more prone to seed remaining uncovered in the furrow, and seeds were placed deeper than in SPST.

As the soil water content becomes wetter there was less likelihood of achieving a fine soil tilth across all tillage types. Sowing in wet conditions occurred in 2007 at the highest soil water content of 35%. In the ST and ZT, the seed in the furrow was inadequately covered by soil which was not as fine in aggregate size as the PTOS. At higher soil water content, there can also be inadequate performance of press wheels and rollers, which prevents proper soil coverage of seeds in furrows and in the ST and ZT methods the walls of the furrow were prone to smearing. Smearing creates a smooth compacted surface which may become a barrier to water movement and root penetration, especially as it dries. During wet conditions of 2007 and the dryer conditions of 2009 with ST and ZT, chickpea seeds were sown deeper than the SPST or PTOS. Deeper sowing of seed in dry conditions will promote emergence, however in wet conditions or with irrigation where soil water content was not limiting, increased depth may delay emergence or inhibit germination (Chapter 3) (Saxena 1987; Siddique and Loss 1999).

In the HBT, sowing occurs at relatively high soil profile water contents but during a period of high temperatures which may promote drying of the soil exposed in the furrow. Soil aggregate size and smeared furrow walls can both affect chickpea establishment under these conditions. The soil aggregate size and soil covering of seed affect the seed-soil contact and the
distributions of pores within the soil matrix. A seed-bed with large aggregates can decrease germination and emergence due to increased drying of the soil, poor seed-soil contact, reduced imbibition and blocking of seedling emergence (Braunack 1995; Rahmianna et al. 2000; Håkansson et al. 2011). In conditions of finer surface tilth, drying of the soil has less effect on germination and emergence due to better seed-soil contact (Rahmianna et al. 2000).

The tendency of the furrow walls to smear under high water contents and the likely drying process within a poorly covered furrow was likely to result in a furrow wall that dries to a hard layer which may inhibit the growth of seedling roots. This combination of factors can limit plant populations as seeds may be delayed in germination due to reduced seed-soil contact and early seedling growth will be restricted due to increased soil strength of the furrow wall and decreasing soil water content (Ellis et al. 1982; Baker 2007b). While soil under the dry layer remains wet, new roots may be unable to penetrate the crust, created from the smearing of the furrow surface, to access available water. The poor crop establishment in ST in 2008 is attributed to this limitation. By contrast, in 2007 smearing was also observed with ST but because the soil remained wet for longer, there was less evidence of impaired emergence or impeded root elongation. However, there would be merit in direct measurement of smearing effects on soil strength around seeds, its relationship to soil water content, and its effects on root elongation during establishment.

5.4.2 Soil water content at sowing

Across the three years of data, the $\theta_e$ at sowing was between 18.6 to 29.4 % and soil strength was below 0.6 MPa (2009) which was within the range where successful germination and emergence of chickpea seeds was established in pot trials (Chapter 3). The seed-bed was created under high soil water contents, which in this soil type can result in very different seed-beds with the different tillage types. Soil strength and porosity are altered with tillage; generally soil strength will decrease and larger voids are created between aggregates. The creation of large voids around larger aggregates can allow increased vapour flow and faster soil drying (Braunack 1995). At sowing, soil water content and soil strength were not limiting factors to emergence of chickpea in these trials, however the shape of the furrow and the
structure of the soil in the seed-bed \textit{viz} surface smearing, aggregate size and seed-soil contact may have impacted on the rate and success of chickpea emergence (Ellis \textit{et al.} 1982; Braunack 1995; Baker 2007b, 2007d).

Of all the growing seasons, 2007 had the highest $\theta_v$ at sowing (35 %). The observed soil conditions (Table 5.2) infer that PTOS was the optimal tillage type for sowing at higher water contents. Emergence numbers were higher in the PTOS compared to the ST or ZT. The PTOS seemed to be better suited to emergence of the chickpea seeds at the wetter soil water content than the other tillage types due to the combination of consistency of seed drop, adequate seed coverage by fine aggregate soil and absence of a smeared furrow wall. Even with soil drying to 28.6 % $\theta_v$, emergence of the chickpea seeds did not improve in the ST and ZT treatment to the level of the PTOS indicating that limitations to emergence still existed. This lower soil water content was similar to the soil water content at sowing in the 2008 trial, where similar seed-bed conditions were observed. In 2008, the $\theta_v$ was 28.7 %. At this water content the SPST treatment covered the seed in the furrow with a variable aggregate size seed-bed (Figure 5.3), with no visible signs of smearing along the furrow wall. In comparison, the ST had sections of the furrow where soil was not thrown back into the furrow covering the seed-bed and the furrow walls were smeared (Figure 5.4). The greater root biomass in the 0 to 15 cm depth, albeit at flowering, may indicate better early root growth of the chickpea seedlings in the SPST compared with the ST in 2008, although the actual time of sampling for root growth was well after the period of early seedling growth. Therefore it is difficult to conclude if the increased root biomass and low SRL in the surface soil of the SPST in comparison to the ST did in fact contribute to early vigorous plant growth of the SPST-sown chickpea plots. However, seedling roots in the SPST were probably less limited by soil compaction directly around the seed than under ST. In summary, the PTOS and SPST were the optimum tillage types for plant establishment in 2007 and 2008 in wet soil conditions. Lower plant populations after establishment in the ST and ZT are attributed to combination of wet soil, deeper seed depth, furrow smearing and irregular covering of the seed by soil.

By contrast with the two previous seasons, in 2009 the $\theta_v$ at sowing was 26.1 %, dryer than the other years. The treatments included a broadcast tillage method which had much lower final
emergence than the other tillage methods. The initial rate of emergence was not as great in SPST as in the ST and ZT; this may indicate that SPST initial conditions around the seed were not optimum for rate of emergence, but with time seeds were able to imbibe water and successfully emerge. In the dryer soil water contents of the 2009 sowing, the difference in final plant establishment among tillage type was minimal among the one-pass tillage techniques. Under the lower soil water content it is suggested that furrow walls were less likely to be smeared and soil covering of the seed was improved in the ST and ZT. The rate of emergence may then be limited by decreased seed depth in the SPST, whereby seeds were sown 2.5 cm in the drying surface soil, requiring more time for the seed to imbibe water for the germination process to begin.

5.4.3 Crop establishment

Initially, the seed rate recommended for the HBT region was 50 kg/ha to achieve a plant population at establishment >33 plants/m² (Saxena 1980a, 1987; Ali et al. 2007). Johansen et al. (2008a) refined this seed rate to 37.5 kg/ha which achieve plant populations from 18 to 32 plants/m². The lower seed rate ensured a more open canopy to minimise Botrytis Grey Mould (BGM) while maintaining satisfactory yield potential. The final emergence numbers in the current tillage type trials varied with tillage type and season. The seed rate used in the present study also varied from 38 to 45 kg/ha. In 2007 and 2008, the PTOS and SPST had greater plant numbers at emergence than the ST and ZT treatments. In 2009, the broadcast tillage established fewer plants than the other tillage types (SPST, ZT, ST). The rate of emergence was greater in the order of ST >ZT >SPST >broadcast in the 2009 trial. The final emergence numbers were well above the recommended number of 20 plants/m², by 200 to 350 % in the 2008 and 2009 trials. In 2007, the final emergence varied across sowing date as well as tillage, and numbers were 20 to 145 % of the recommended rate. These differences in final emergence number and rates of emergence may be attributed the soil water content at sowing, and to characteristics of the furrow and seed-bed produced during tillage as described in the previous section. In addition the planter machinery underwent continuous development over the three years to improve seed drop, soil coverage of the seed and soil-seed contact by improved press wheel or
roller design (Johansen et al. 2012). This improvement in design would in part contribute to the improvement in emergence from 29 plants/m², the maximum in 2007, to 68 to 81 plants/m² in 2009. Collectively, the three years of sowing suggest that with minimum tillage techniques lower seed rates could be satisfactory to achieve the target plant populations required in the HBT although further confirmation of this conclusion under wet soil conditions with the most recent version of the planter is advisable.

5.4.4 Soil drying in the surface seed-bed during emergence

Evaporation of water from the soil surface occurs in three stages (Bond and Willis 1970). Stage 1, evaporation from a wet soil, is at the potential evaporation rate similar to a free water surface, and evaporation is at a constant rate. Stage 2, is where the soil has become dry and the rate is limited by water flow to the surface and the rate of drying decreases. During stage 3, a very low constant rate of evaporation occurs, where water loss is controlled by dry surface soil and water loss is by vapour diffusion (Bond and Willis 1970; Steiner 1989). Transition from the 1st to the 2nd stage is when the initial dry soil surface layer begins to impede evaporation (Flury et al. 2009). In the present study, our aim was to decrease the loss of water from the surface soil to ensure adequate soil water at sowing for germination and emergence of chickpea.

Increased levels of tillage have been reported to decrease surface soil water content through the drying of exposed soil after tillage (Rahmianna et al. 2000; Schwartz et al. 2010). By contrast, in 2009 the fallow treatment with no tillage dried the most during the establishment period. Conversely the treatments with full tillage and most soil disturbance, creating aggregates and macropores, dried least. These differences occurred at a time when the soil surface was bare and therefore evaporation rather than plant water use was the primary source of loss of water from the soil.

The drying recorded in the surface 0-6 cm of soil included the tilled layer of soil, within which the seed was placed. The tillage and sowing techniques may also have altered the levels at which the within-furrow measurements were taken by the probe, with measurements slightly deeper than the original soil profile depths at sowing, and in the fallow treatment. However, the measurement was from the layer of soil where the seed was placed; therefore this was relevant
to soil water content around the seed. Methodologies which separate the depths of measurement into smaller increments may better show soil drying in the seed zone (Rahmianna et al. 2000). The 0-6 cm measurement probably reflects a combination of processes which may be contributing to water loss in the seed-bed. Drying of the surface occurs due to evaporation of water from the soil surface. After sowing, evaporation may correspond to the 2nd stage, and the movement of water through the soil and evaporation is controlled by below surface soil conditions (Flury et al. 2009). The creation of more, larger pores, due to cultivation breaking surfaces and aggregates may slow soil water movement upwards by limiting capillary action in the soil matrix. An air-dry surface layer can minimise the evaporation rate from a soil (Bond and Willis 1970).

The ZT treatment exhibited greater water loss than other one-pass planting methods, which is attributed to the open furrow with poor soil coverage which allows vapour loss (Baker 2007b). In addition, like the fallow treatment, most of the soil surface in the inter-row space was undisturbed which would allow capillary movement of soil water to the surface for evaporation. By contrast, the other tillage systems essentially produced a surface soil mulch which was effective in conserving seed-zone soil water (Wuest 2010), across the entire sown surface in the broadcast and SPST treatments but mostly above the sown furrow in the ST. These other tillage treatments had slower loss of water over time, and may be exhibiting the effect of disturbed soil which has broken the pathways of water movement via capillary rise and therefore the water within the layer has been conserved (Baker 2007b). The soil water content at 6-12 cm, deeper than the tilled layer, was not different among tillage types and did not vary with time among tillage methods after sowing. This indicates that evaporative losses during the establishment period were confined to the surface, and not affected at depth by tillage type. Schwartz et al. (2010) also found that the water content below the surface soil (>20 cm) was not influenced by tillage. In a year such as 2009 when no in-season rainfall occurred the surface soil disturbance caused by broadcast, SPST and ST may be an important mechanism for conservation of water in the soil seed-bed and soil profile and for early vigorous seedling growth.
Surface standing stubble and mulches have been found to reduce surface soil water loss, decrease surface soil temperature and increase seedling emergence of crops (Radford and Nielsen 1983; Steiner 1989; Olasantan 1999; Pervaiz et al. 2009; Murungu et al. 2011). In humid regions with high soil water contents, mulch has no advantage in conserving surface soil water content or emergence success (Rahmianna et al. 2000). Residue retained on the surface decreases the heat absorbed by the soil by reflecting sunlight and reducing the transfer rate of water vapour from the soil to the atmosphere, reducing water loss during the 1st stage of evaporation (Wuest and Schillinger 2011). With a greater amount of residue on the surface, evaporation rates in the 1st stage of evaporation will decrease (Bond and Willis 1970). The 2nd stage of evaporation is not as affected by surface residue since the rate of evaporation is controlled by the conductivity of water and water diffusivity below the surface (Wuest and Schillinger 2011). Differences in evaporation among surface residue treatments have been found to be lost after 10 days (Aase and Tanaka 1987). In the short period from rice harvest to chickpea sowing, in relatively wet soil in the HBT of Bangladesh, any conservation of soil water in the seed-bed may be enough to increase the sowing window. When the surface of the soil was covered by the rice mulch in 2008 the loss of water was not as great as in the standing stubble treatment. The standing stubble treatment showed greater variation of the soil water content in response to the influences of temperature, humidity, and fog. However, the rice straw mulch layer was removed after a very short time due to farmer requirements. Had the mulch layer remained on the surface for longer, a greater difference between the soil water content of the rice mulch treatment and that of the standing stubble treatment may have been found. However, since the soil water contents at sowing across the trials in 2007-2009 were high, a series of drier seasons would be needed to adequately test the effectiveness of a mulch cover to conserve moisture. It is suggested that mulching would be most effective if a farmer envisaged sowing a rainfed crop a significant number of days after rice harvest.

The surface drying of the fallow in 2009 (Figure 5.12) indicates that over 28 days from rice harvest to the 20 December, just after the recommended cut-off date for sowing chickpea, the 11.7 % loss of water from the surface to a $\theta_v$ of 17.7 % would have resulted in sowing into a seedbed below optimum for chickpea germination and emergence (Chapter 3). In such cases,
return of straw to the field after threshing may be a feasible option to conserve surface soil water. Alternatively, retention of more crop residue at harvesting under conservation agriculture practices may benefit crop establishment by conserving seed-bed soil water content. The effectiveness of standing stubble for conserving soil water in the HBT for improved minimum tillage establishment of rabi crops needs further investigation. However, as reported in other studies, competing uses of stubble for fuel and fodder, which are often the priority in farming systems in the HBT, restrict the amounts of residue retention possible as part of this management (Sommer et al. 2011).

5.4.5 Crop water use

Minimum tillage is a practice often used to conserve water in the soil profile and it has been reported that in conditions of less tillage there was greater soil water storage in the profile or greater soil water storage at depth in the profile later in the growing season (Horn et al. 1996; Barzegar et al. 2003). Others have reported no change in profile SWC among tillage systems and have attributed that to the practice of minimum tillage being in place for only a short duration (years) (Licht and Al-Kaisi 2005).

During 2008 and 2009, \( \theta_e \) was measured to depth in the soil profile. The water stored in the top 40 cm was 101 and 85 mm, respectively, in 2008 and 2009. At podding for both years the \( \theta_e \) were less than 10 % leaving very little water remaining in the 0-50 cm layer for pod-filling and finishing. In 2008, there is evidence of root growth and extraction of water at 50 cm depth between 23 January and 23 February. In 2009, at harvest the profile SWC was similar to the previous measurements at podding (Figure 5.17), indicating soil water stores had previously been exhausted from this depth. The high yields and very low profile SWC at podding in 2009 suggest that plant roots were able to access water deeper than 60 cm in the profile and avoid drought. This illustrates the chickpea plants’ drought avoidance trait of deep root growth (Ali et al. 2007). It may also indicate that osmotic adjustment, another mechanism of drought resistance found in chickpea, allowed the chickpea to maintain high yields at low profile SWC with no additional rainfall (Leport et al. 1998; Leport et al. 1999; Turner et al. 2001). This may also be supported by evidence that \( \theta_e \) in the root zone (0-60 cm depth) was less than 10 % at 20
February, indicating osmotic adjustment may have already allowed the maximum water extraction in the surface of the profile. Chickpea plants are able to grow roots to depths of up to 90 to 105 cm in the soil types common in the HBT (Ali et al. 2005; Ali et al. 2007). The total water use of chickpea to reach yields comparable to those in 2009 have been reported to be between 110 and 270 mm (Saxena 1984; Siddique et al. 2001). This indicates that in 2009, where total water use from sowing to harvest in the top 50 cm was only 69 mm a significant proportion of water was extracted from deeper in the soil profile. The extraction of water due to evaporation and any weed infestations was indicated by the decline in subsoil SWC in the fallow treatment in 2009 (Figure 5.16). During the period to 20 February, in the fallow treatment water had been removed from the top 20 cm of the soil profile only, but by the time of harvest of chickpea from the other treatments, water had been removed by evaporation and weeds to 40 cm depth.

The profile SWC during the season indicate that the chickpea plants sown in 2008 also would have needed to extract water from deeper in the soil profile as the season progressed. The lower yields in 2008 (compared to 2009) indicate that there were other factors limiting chickpea growth. This may have included the lower early vegetative growth in 2008 compared to 2009, temperatures which were too high or low at different growth stages (which are discussed further in the following Section 5.4.7) and the low plant population for the ST.

In 2009, the broadcast tillage system had \( \theta_v \) at podding similar to the fallow treatment, but greater than the minimum tillage treatments (ST and ZT) at >40 cm. This may be attributed to the lower plant numbers, pod number and biomass of the broadcast-sowing which extracted less water to depth compared to the other tillage systems. This indicates that chickpea plants in this treatment used less water in the vegetative growth phase. The different extraction patterns of water at depth through the season mirror the plant density. This is an indication that modification of plant density and configuration (plant spacing between and within-rows) of chickpea plants may allow conservation of soil water in the profile in the season, so water allocation to the plant can be maintained through reproductive growth to harvest. Manipulations of this sort have been found to leave an allocation of water at depth or between the rows of plants which can be accessed later in the season. Hence the findings from the
Merredin trial (Chapter 2) with wide row spacing may have relevance to chickpea production in the HBT. However, as in WA, the benefits of wide row spacing may depend on the available soil water. By contrast with WA where pre-sowing soil water had less effect on chickpea response to wide rows than in-season rainfall, in the HBT the stored pre-sowing soil water is the main source of water available for crop growth. Hence further investigation is warranted to determine whether wider rows can improve chickpea yield in the HBT when soil water content at sowing is limited.

The various one-pass tillage treatments in the 2009 study had similar plant numbers and profile SWC. When the plant numbers were less in the ST compared to SPST treatments in 2008, the profile SWC did not show any difference with depth, or with time. Root growth data (2008, Figure 5.8) indicated that while there were more roots in the 0-15 cm depth in the SPST relative to the ST, at the times of measurement of water content there was no difference in water content of this profile depth between the tillage types. The SRL indicates that the roots at >45 cm depth in the SPST sown crop were longer and thinner than the ST sown crop, and therefore may have been able to spread further into layers to access more water later in the season. In a range of pulse species, Kar and Kumar (2009) found that there was greater extraction of water to depth with increased root length density. This extraction of water was also greater at depth with increased tillage and this was considered to be due to rapid surface depletion of soil water in this treatment which meant the plants needed to extract water from deeper in the soil profile later in the season.

5.4.6 Crop growth and yield

Grain yields across the three seasons were between 227 and 1817 kg/ha for the one-pass tillage sowing and 1087 kg/ha for broadcast-sowing (2009 sowing only). Final yields varied among seasons, with the 2009 being the most successful year with all tillage types having grain yields greater than 1000 kg/ha. The potential yield of chickpea in the HBT is >2500 kg/ha (Johansen et al. 2008b), but the yields of chickpea in farmers’ fields with a broadcast system are generally 500 to 700 kg/ha. With traditional hand broadcast-sowing and bullock-drawn plough (1 pass) and laddering (2 passes), Ali et al. (2007) achieved yields of 1400 kg/ha. In
experiments where seed priming was investigated, chickpea yields were 1020 to 1450 kg/ha and in farmer demonstration plots were from 430 to 1200 kg/ha (Musa et al. 2001). This range in chickpea yields indicate that high yields are possible with minimum tillage technology in comparison to the broadcast system, and in the cases where yields are comparable to the broadcast system, the benefits of savings to the farmer in regards to labour, input costs and time (Haque et al. 2004; Justice et al. 2004) mean that the minimum tillage technology should be attractive for adoption by farmers. In eastern India, reduced tillage improved yields of post-rice rabi season crops over ZT and a relay cropping method (Kar and Kumar 2009). Relay cropping entailed broadcasting seed directly on a wet soil surface before harvest of the preceding crop. The number of passes of cultivation with the conventional tillage was 5 (2 x harrow, 2 x cultivator, 1 planking), and the reduced tillage was 2 tillage operations by country plough (5 days apart). The reasons for the greater yields were cited as better germination, less weed infestation and greater infiltration of rainwater in the reduced tillage treatment. In addition there was rapid depletion of water from the conventional tillage soil profile during land preparation and less available water later in the season. These results are from a region which also relies on the use of residual soil water and minimal rainfall during the season. The mean in-season rainfall, 59 mm, was beneficial to the crops where tillage caused more disturbance of the soil surface, which can improve infiltration.

The yields for the 2009 season, regardless of tillage type, were much greater than yields from the 2008 and 2007 tillage trials and the time of sowing trials described in Chapter 4. However, profile SWC would not have been a reason for the improved yields. At sowing, profile SWC in the 2009 tillage trial was similar to the values in other trials in 2007 (sowing date (SD) trial) and 2008 (tillage type (TT) trial), while at podding profile soil water content in all years was close to wilting point. Moreover, in 2007 and 2008 there was minimal in-season rainfall while in 2009 there was none. The improved design of the tillage machinery and training of operators could be part of the explanation. Seed metering and seed drop became more consistent and the operator had increased awareness of the seed-bed conditions required and could operate to limit adverse conditions. Other factors, such as plants number and weather
during the growing season also impact on the final yields. In no year did pod-borer or BGM affect crop growth.

No tillage type consistently showed greater rates of plant establishment (Section 5.4.3) or grain yields. In 2008, grain yield of SPST was greater than ST and in 2009 grain yield of the one-pass tillage techniques (ZT, ST, SPST) were all greater than in the broadcast. In the seasons of 2008 and 2009, much of this difference may be due to the greater number of established plants, which involved an additional 22 to 26 more plants/m² in the higher yielding treatments. The crop growth parameters measured within the season and at harvest were always consistently greater in the treatments with higher plant number and final yields in 2008 and 2009. Increased PPD and biomass production has been found to be correlated with grain yield (Siddique and Sedgley 1986; Jettner et al. 1999; Liu et al. 2003).

The greater grain yield in the SPST compared to the ST in 2008 was attributed to the greater number of plants, the early vigorous plant growth, and greater biomass of the shallow roots leading to consistently greater biomass throughout the season. In addition the higher SRL indicates that the roots at >45 cm depth in the SPST sown crop exhibited differences (longer and thinner) that may have allowed extraction of more water deeper in the profile.

By contrast, in 2007 the SPST treatment had more plants per square metre (mean difference of 5 to 9 plants/m²), but grain yield was less than the ZT and ST. The ZT and ST treatments had lower plant densities but were able to compensate for this through greater plant biomass, pod numbers and grain weight per plant. This indicates there was a degree of morphological plasticity in the growth of the chickpea plants in 2007 with ZT and ST, demonstrated by the increase in plant biomass parameters and increased pod numbers per plant at lower plant populations which have led to higher yields (Saxena and Sheldrake 1974; Siddique et al. 1984). Plant population density was within the recommended range in the SPST treatment (<30) and there were no observations of disease or insect damage to this tillage type over the other tillage types.
5.4.7 The effect of weather parameters on crop growth

The grain yield of the chickpea sown by ST in the 2008 tillage type trial sown crop was similar in yield to the chickpea crop sown on the same date in the 2008 sowing date trial (Chapter 4) (251 kg/ha compared to 350 kg/ha). The grain yield of the chickpea sown by SPST in the 2008 tillage type trial was greater (559 kg/ha) and was in the higher range of the yields of the 2008 sowing date trial, which were sown 2 to 4 days later. In terms of limiting temperature conditions during crop growth, the 2008 tillage type trial was within non-limiting minimum or maximum temperatures as was the 2008 sowing date trial sown at the similar time. This was discussed in Chapter 4.

Increasing temperatures above 30 °C along with water stress limit growth of chickpea grown without irrigation (Roberts et al. 1985). High temperature (35 °C day) during vegetative and reproductive growth can limit pod fertility, seed set and seed yield (Summerfield et al. 1984; Wang et al. 2006). Mean temperatures indicate that the 2009 tillage trial did not encounter detrimental temperatures during the growing season, as was reported for the later sown 2009 SD trials (Chapter 4). Plant establishment was similar for the 2009 SD trial and the broadcast tillage treatment in the 2009 tillage trial. The following discussion on limitations to growth in relation to temperature is particularly pertinent when these trials with similar plant numbers are considered. For the 2009 tillage type trial which was sown on 25 November, the mean temperature from sowing to flowering was 17.9 °C, with the crop experiencing temperatures less than 15 °C for much of January, resulting in a long vegetation growth phase of 73 days. During the period from podding to maturity (38 days) the mean temperature was 25.3 °C, and maximum temperatures were less than 35 °C for most of the period of reproductive growth. In comparison the later sowing dates (14 and 22 December) in the 2009 SD trial (Chapter 4), had mean temperatures 3.7°C greater during reproductive growth and a significant proportion of the time spent in reproductive growth was at maximum temperatures greater than 35 °C. Such effects of temperature may account for some of the difference between the two trials which were sown with the same machinery, same operator, on opposite sides of a roadway in essentially the same soil type. An indicator that the 2009 tillage type trial was under less temperature stress during reproductive growth was the lower proportion of unfilled pods.
reported (13 %) across all the tillage types in comparison to the last sowing dates of the 2009 SD trial where high temperature most likely had an impact and 29 % of pods were unfilled. Temperature regimes of 35/26 °C (day/night) during reproductive growth have been found to decrease pod number, seeds per plant and seed weight (Wang et al. 2006). In this present study, where 29 % of pods were unfilled the mean maximum and minimum temperatures during reproductive growth were 36/23 °C which was within the range Wang et al. (2006) found limited reproductive growth of chickpea.

5.5 Conclusion

With the introduction of mechanised planters that allow row-sowing with one-pass of the tillage machinery in the HBT of Bangladesh, seeding is more likely to take place at higher surface soil water contents than has been reported under the traditional broadcast system. This mitigates the limitations of a dry seed-bed at sowing that farmers normally associate with a rabi season crop sown after harvest of the rice crop. With timely sowing using one-pass machine planting, the soil water contents in the seed-bed were not limiting for germination of the seed in the present study over three consecutive years.

Different tillage types operate best at different optimum soil water contents. The more thorough tillage techniques create a better seed-bed under the higher soil water contents. The tillage type which seemed to have the least risk associated with germination and emergence of the chickpea seed was the SPST, which cultivated the entire surface soil of a field. With the ST and ZT under the higher soil water contents there is potential of smeared furrow walls and poor soil covering of the seed in the seed-bed which can limit seed-soil contact, and increase soil compaction directly around the seed that decreases both seed germination and/or the rate of emergence. These limitations could be mitigated by sowing at appropriate $\theta_v$ for minimum tillage on each soil type and with further development of rollers or press wheels. This was demonstrated at the lower, but still adequate, soil water levels in 2009 when final emergence and grain yields were similar regardless of the tillage type.

The rate of soil drying in the seed-bed changes with tillage technique. Uncovered furrows and the fallow soil lost more surface soil water than the other seed-beds created with variable
levels of soil disturbance. Where delays to sowing occur the use of surface mulch may conserve soil water in the surface, as substantial amounts of soil water can be lost before and after sowing from an undisturbed soil surface.

The benefits of early mechanised sowing (Chapter 4) have been validated, as early sown chickpea crops matured before maximum temperatures affect pod-filling. In addition, the soil water content in the soil profile was $<10\% \theta_v$ to 50 cm depth at podding, indicating any additional conservation of water in the profile due to early sowing would be an advantage.
6 General discussion and conclusions

This thesis investigated the soil water constraints for chickpea production in its two main rainfed growing environments: Mediterranean-type environments and the summer-dominant rainfall environments. In both growing environments, water stress can occur at crop establishment, during vegetative growth or during reproductive growth. The two climate types were represented in this thesis by south-west Western Australia (WA) (Mediterranean-type environment) and the High Barind Tract (HBT) of Bangladesh (summer-dominant rainfall environment). In south-west WA, the agricultural system is mechanised and has substantially applied minimum tillage and conservation agriculture principles to crop production, whilst in the HBT mechanised row-sowing techniques have only recently been introduced allowing the development of minimum tillage cultivation to be introduced in the region.

In south-west WA, the thesis investigated ways of maximising water use efficiency of the chickpea crop in an already established mechanised, minimum tillage system, where crop agronomy and management are well researched already. However, by manipulating row spacing and plant population density (PPD), there may be opportunities to optimise crop water use throughout the growing season. This thesis examined how row spacing interacts with differing starting soil water profiles.

In the HBT, investigations focused on identifying when the chickpea crop is best sown in the rabi season with mechanised row-sowing, which method of mechanised row-sowing from full tillage to zero tillage would allow the best crop establishment, and if the different tillage techniques influenced final crop yield. In addition to water stress, the chickpea plant may also encounter temperature stress and adverse soil physical properties which can further exacerbate any water stress and limit crop growth.

During this study, the abiotic stress of temperature (both low and high) was identified as a constraint to chickpea growth. Specifically, the work identified when the chickpea crop was under temperature stress during the growing season in the HBT. Identifying the periods during chickpea growth when temperature constraints are limiting is important, as there is scope to
vary sowing time in the HBT to allow sowing into soil physical conditions optimal for crop establishment whilst also ensuring favourable temperatures for subsequent growth stages.

6.1 Alleviation of drought stress – plant population density and row spacing

As identified in Chapter 1, modification of PPD and row spacing are agronomic crop management techniques which may prevent or delay the onset of drought in rainfed environments (Katyal and Vittal 2003). It does so by manipulating rates of evapotranspiration so that soil water remains available towards the end of crop growth to favour pod-fill and seed set. Drought stress is often cited as the most limiting stress to chickpea crop growth across all rainfed environments where it is produced. In recent reviews, row spacing and PPD are discussed as management tools to improve water use efficiency in rainfed cropping systems where crops are prone to drought (Sadras and McDonald 2012; Siddique et al. 2012).

Growing season rainfall determined whether wide or narrow row spacing improves grain yield of chickpea (Chapter 2). With higher than average growing season rainfall, the narrow rows yielded higher whilst in the dryer season the yield increased with an increase in row spacing from 23 to 50 cm. Adding water to the soil profile before sowing was used to simulate summer rainfall events (in south-west WA) that may add to stored soil water before the sowing of the crop. This did improve crop yields even though the additional amount of water stored in the soil was relatively small. After irrigation of 75 to 80 mm there was only 14 to 20 mm/m of additional water in the soil profile. This confirms that pre-season rainfall sufficient to add about 20 mm or more stored water to the profile can improve yield potential. The importance of pre-season rainfall to wheat yields across southern Australia has been confirmed by Hunt and Kirkegaard (2011). They estimated (through crop simulation modelling) the contribution of summer fallow rainfall (SFR) (November to April) to wheat yield across southern Australia and found that SFR contributed from 3 to 72% to yields, depending on rainfall distribution and soil type differences among sites. Across sites in south-west WA, 19 to 28% of SFR was stored in the soil profile for crop use. In addition, in the 10 years from 1999 to 2008 there was less growing season rainfall and/or more SFR than in the 110 years previously. The result of this is that SFR contributes more to grain yield than previously, with the mean contribution of SFR to
grain yield being from 3 to 25 % across south west WA (Hunt and Kirkegaard 2011). The utilisation of SFR is therefore of growing importance across the region.

Ward et al. (2013) showed that the intensity of rainfall events and the percentage of clay in the soil will directly affect the proportion of rainfall retained in the soil profile or evaporated. Soil with higher clay percentage and water holding capacity will hold the water from SFR in the surface soil where it is prone to evaporate (Hunt and Kirkegaard 2011); rainfall events of greater than 25 mm are required to ensure infiltration of rainfall such that it is retained in the soil profile. In the 2008 trial (this thesis), the 75 mm of pre-season irrigation was split over 26 days and ten events. The resultant additional water in the profile, 14 mm, indicates that the combination of many irrigation events of small volume (5 to 15 mm) on a high clay soil (38 %), were not large enough for water to infiltrate deeper into the profile and a substantial proportion of applied water was lost to evaporation (Hunt and Kirkegaard 2011; Ward et al. 2013). Even so, the additional 14 mm in the profile at sowing did improve chickpea grain yields by a mean of 365 kg/ha indicating that SFR will also be of advantage to chickpea crops sown across south-west WA.

In the 2008 season it was deduced, from monitoring soil water content and evapotranspiration through the season, that chickpea plants sown at different row spacing and PPD allowed different rates of soil evaporation across the inter-row space and that the plants accessed soil water differently at different planting configurations. The different rates of evaporation from the soil were inferred from the differences in cumulative evapotranspiration with distance across the inter-row space. This difference was most obvious at the widest row spacing (75 cm) early in the season when the crop canopy had not spread to the middle of the row and evapotranspiration was the same in the inter-row space for both irrigation treatments. The differences in cumulative evapotranspiration between the irrigated treatments and between the rows at the wider row spacing have been related to biomass production. Soil evaporation is decreased with high crop biomass and less exposure of the surface soil to direct solar radiation (Yunusa et al. 1993; Zhang et al. 2000). Direct measurement of soil evaporation using lysimeters and parameters related to canopy cover and radiation interception would confirm these inferences.
Monitoring the soil water profiles between the rows of the chickpea plants in 2008 provided insight into how plants used water between the rows. At the 12 cm distance from the plant rows in the treatments without additional pre-season water, the plants sown at 23 cm row spacing used more of the available water than the plants at the wider row spacing. This comparison may have been confounded by the difference in PPD in the 23 to 75 cm row spacing but was not confounded between the 23 and 50 cm row spacing treatment which had similar PPD. In addition, the crops with pre-season irrigation had greater biomass production and used more available water, whilst the chickpea in the non-irrigated treatments had less available water early in the season and more available water later in the season which the chickpea plants did not utilise. Indeed chickpea plants in both irrigation treatments developed water stress during pod-fill. In the pre-season irrigated crop, later in the season there was no plant available water whereas in the non-irrigated treatments water was available a depth in the profile, but plant roots were unable to access it. Further investigation to monitor plant root growth may answer the question of whether root growth parameters such as length, volume and density were also limited and if there were any differences to plant root growth both horizontally and vertically to the middle of the rows between treatments. Analysis of soil water in the profile was completed in 2008, the season with above average growing season rainfall. Similar measurements for a season with below average growing season rainfall may help elucidate why in the dry season (2007) additional soil water in the profile at sowing did not change the trends in grain yield with row spacing. The interaction between pre-season water content and row spacing may reveal a different response for plant water uptake under below average growing season rainfall.

The studies in south-west WA showed that growing season rainfall had a greater effect on the response of chickpea to row spacing configuration than starting soil water content of the profile. Turner (2011) reviewed the improvements in wheat yields across south-west WA under declining rainfall and outlined the importance to crop yields of maximising efficiency of growing season rainfall. This was termed precipitation use efficiency (PUE), and was the result of maximising the use of rainfall by the crop through greater crop transpiration and less loss by soil evaporation. These improvements in PUE and resultant crop yields may not be limited to wheat but also have relevance for other crop species such as grain legumes. Improvements to
PUE will minimise water deficits and increase grain yields and can be attributed to advances in crop genetics (deep root, osmotic adjustment, transpiration efficiency and greater assimilate redistribution) and crop agronomic management techniques (weed control, minimum tillage, early planting) as identified by Turner (2011). Siddique et al. (2012) also identified the following agronomic management techniques that minimise the effects of drought on grain legumes: fertiliser use, crop rotation, fallows, and water conservation methods; these techniques would also improve PUE. Precipitation use efficiency was altered with the changes in the planting configuration of the chickpea crop in 2008 due to crop agronomic management. It seems that the plants with greater growth early in the season due to access to stored soil water had better PUE. In contrast, the plants with access to less soil water early in the season were also unable to use the available soil water later in the season. In addition to losses of rainfall to evaporation, PUE was further decreased as the chickpea plants could not access water deeper in the soil.

From the results of the WA trials, optimum PPD and row spacing for chickpea may be hypothesised for the HBT of Bangladesh. The conditions in the HBT may have parallels in the pre-irrigated, low in-season rainfall conditions of the 2007 row spacing trial in south-west WA. The rainfall during the rabi season in the HBT is minimal, but starting profile soil water content is high. In the HBT of Bangladesh with lower PPD, the extraction of water from the soil profile was inefficient, leaving plant available water in the soil profile later in the season. The low growing season rainfall is an indication of a low yield potential, and from the 2007 and 2008 trials in south-west WA it was found that high starting soil water content does not favour particular row spacing configurations. It could therefore be hypothesised that in the HBT of Bangladesh, with low growing season rainfall and low yield potential, planting at wider row spacing may result in higher yields with greater reliability of occurrence. Recent improvements in mechanised row-sowing in the HBT allows greater reliability at sowing for controlling seed depth, seed rate and soil coverage of the seed. Hence the possibility now exists to conduct trials in the HBT to investigate the PPD and row spacing configurations which will produce reliably higher yields. The soil water remaining from the monsoon rainfall in the months before sowing of the rabi season crop is the dominant contributor to plant available water in the summer-
dominant rainfall environments. Hence understanding how variation in pre-sowing profile water storage interacts with PPD and row spacing could open up the possibility of higher water use efficiency for rabi chickpea crops in the HBT. Moreover, further advances in chickpea crop genetics and crop agronomy to minimise periods of soil water deficit and maximise plant water use will benefit chickpea production in both the Mediterranean-type environment and summer-dominant rainfall environment.

6.2 Alleviation of drought stress – crop establishment

This thesis furthered understanding of the soil physical properties that limit chickpea establishment. By defining limiting thresholds of soil water, soil aeration and soil strength for chickpea germination and emergence in pot trials it was possible to predict when these factors were limiting in field conditions in the HBT. The rate of soil drying in the 2007 to 2009 seasons was less than predicted in previous reports which had concluded that a dry soil surface was the major impediment to chickpea crop establishment (Musa et al. 2001). Such understanding has guided the development of minimum tillage and mechanised sowing techniques for the hard-setting soils of the HBT and similar soils (Haque et al. 2010). With the improved mechanised sowing technology, the time between the harvest of the previous rice crop and the sowing of the following chickpea crop can be decreased; therefore the perceived limitation of a dry seed-bed limiting chickpea establishment which may be valid for traditional broadcast methods seems less likely under mechanised sowing.

The water content of the surface soil at sowing during the 2007 to 2009 seasons in the HBT was 15.2 % and 23.9 % (g/g) (Chapters 4 and 5), levels which did not limit chickpea germination or emergence in the pot trials (Chapter 3). In addition the field measurements of soil strength were in the ranges of 0.38 to 1.99 MPa directly before sowing, 0.45 to 0.72 MPa in the seed row after sowing and 1.5 MPa when monitored after final emergence (Chapter 4). With the later sowing date in each season, soil strength increased due to lower soil water contents. In the pot trial, soil strength began to impede root growth at >1 MPa. The values in the field trials indicate that directly after sowing, soil strength was not limiting in the seed bed. After emergence, with continued soil drying in the seed-bed, soil strength could have been
limiting to root growth. However, following emergence the roots of the chickpea plant should have grown out of the cultivated layer and into uncultivated soil. Soil strength would then depend on the soil structure and soil water content of the uncultivated soil. The bulk density of the 10 to 15 cm layer in the field was 1.4 g/cm$^3$ and soil water content was between 13 to 17 %.

Results from the pot trials indicate that at these values elongation of the main root downwards and lateral root growth should not be limited in field conditions.

In this thesis the soil physical requirements of chickpea seeds for germination were studied in the context of the soil and environment conditions found in the HBT in the rabi season which linked known requirements for chickpea emergence from pot trials to environment conditions. Other researchers have investigated how chickpea genotypes differ in their emergence characteristics with soil water content, to identify genetic characteristics which allow germination under rainfed conditions with low soil water content (Hosseini et al. 2009a; Vessal et al. 2012). Hosseini et al. (2009a) reported that at uniform soil water content, emergence success and characteristics of emerged seedlings varied among chickpea genotypes. Vessal et al. (2012) noted that the variation among chickpea genotypes in emergence under sub-optimal soil water content could be exploited to identify tolerant chickpea accessions with improved seedling growth. To do this Vessal et al. (2012) developed an assay system under which chickpea seeds were placed in very low (10 % of field capacity) soil water conditions and germination monitored. Using this system the gene expression for early germination could be identified and this would aid in the identification of upregulated or down-regulated genes associated with germination under water-limited conditions. These two approaches to improving chickpea crop establishment in water limited conditions (one an agronomic solution, the other a genetic solution), when combined will improve the knowledge of matching chickpea genotypes with soil conditions and time of sowing.

The addition of a surface residue of harvested rice straw was tested in the present study to determine if the rate of surface soil drying could be slowed. The use of mulch did retard evaporation of water from the soil surface. However, the mulch was removed after only four days, not long enough to determine if the extra retained soil water would benefit a later sown crop. Since the soil water contents in the surface soil were found not to limit chickpea
establishment across the years of this study the use of a mulch treatment to conserve soil water may not be warranted except in drier topsoil conditions than encountered in the present study. Under drier topsoil conditions, a mulch cover to conserve water in the surface soil should extend the window of time available for sowing which may be beneficial if soil water content required for crop establishment is considered alone. However, as discussed below temperature limitations also need to be considered when selecting an optimal sowing date.

6.3 Alleviation of drought stress – cultivation practices

Throughout the course of this study the minimum tillage planters underwent significant modification in design and capability. This resulted in variations to machine weight and set up, seed metering devices, seed covering devices and the mounting of seed and fertiliser boxes on the seeder. As the development of the machinery progressed and the machine operators improved their knowledge of the sowing machinery and appropriate sowing conditions, there has been increased homogeneity across the field in terms of seeding depth, seed rate and seed coverage by soil, which resulted in greater PPD. Across the seasons this did not necessarily translate to higher yields due to overriding seasonal weather factors affecting chickpea growth and the morphological plasticity exhibited by chickpea plants in relation to PPD. However, this greater reliability in sowing which will lead to greater success of chickpea establishment provides the opportunity for more controlled investigation into manipulating PPD and row spacing to achieve reliable yields. The final PPD in a field will affect the incidence of pests and diseases, and weed competition, as well as crop water use during the different growth stages of the crop (Whish et al. 2002; Turner 2004; Johansen et al. 2008a; Peltzer et al. 2009). At present the seed rate used is that developed for broadcast seeding. With mechanised seeding and row-sowing, the optimum seed rate needs to be determined to achieve the PPD that both optimises plant water uptake throughout the season and limits the incidence of pests, diseases and weeds.

Of the tillage techniques being developed in the HBT, the single pass shallow tillage (SPST) consistently covers the seed in the furrow with a layer of soil, but the aggregate size of the covering layer depends on the soil water content at the time of sowing. A dryer soil will have a finer aggregate size and tilth, whereas at wetter soil water contents the aggregates will be larger.
The strip tillage (ST) only has cultivation in the seed furrow but some of the cultivated soil is thrown out of the seed furrow which may result in inadequate seed covering unless seed depth is adjusted. The zero tillage (ZT) system has no cultivation, as the only soil disturbance is due to the seeding furrow opener which is pulled through the soil. In both the ST and ZT systems covering the seed with soil is often inadequate in wet conditions as the soil tends to be remoulded rather than broken or shattered, leaving few loose aggregates dropping into the furrow as a covering for seed. In the ZT system, in the uncovered seed-bed the smeared soil will dry and may harden to limit root growth. By contrast, in a seed-bed that is well-covered with soil, there will be less soil drying and root penetration to the subsoil is more likely to be completed before topsoil drying is too advanced. Such conditions were observed in the field during the 2009 tillage type experiment (Chapter 5) when the ZT treatment did have greater soil drying in the seed-bed than the other cultivation techniques which had better consistency of soil cover over the seed. Further soil water measurements of the seed-bed and observations of initial seedling growth are needed to demonstrate that poor seed covering by soil and increased soil drying in the seed-bed are limiting chickpea crop establishment. Further measurements of soil strength around the seed and across the smeared walls of strips and furrows are required so the level of resistance imposed on radicle elongation can be quantified and related to tillage type, soil type and soil water content.

In the sowing conditions across the 2007 to 2009 seasons, surface soil water content was wetter than expected. Wet soil is more likely to be smeared by the force of furrow openers than soil at field capacity. The greater disturbance of soil during SPST and ST restricts smearing by the furrow openers, due to the breakup of the soil by the rotating tines in front of the furrow openers. However, smearing under these tillage methods may also be underestimated since smeared layers will be mostly obscured by the soil covering the furrow. Regardless of the tillage type used the placement of seed on a smeared surface has the potential to limit early root elongation into the soil below. In this study the measurement of soil water content and soil strength was for sampling depths 0-6, 6-10 cm or 0-2.5, 2.5-5 and 5-10 cm, respectively. These depth increments are probably too coarse to describe the conditions limiting seedling emergence and root elongation. While smeared surfaces were observed during sowing in this study,
measurements did not determine if the smearing altered soil strength at the smeared surface or directly below the smeared layer. There are significant difficulties in measuring the properties of a smeared layer. Firstly, after tillage they are difficult to locate. Secondly the process of removing soil to locate the smeared surface may disturb the smeared zone and lead to artefacts in the measurements. Moreover, very shallow depth increments of soil would need to be sampled to measure soil water content, and a fine-scale penetrometer required to determine if the smearing does change soil strength. Where smearing is likely to occur in wet conditions the soil is also prone to compaction directly around the furrow (Baker 2007c). The tendency of the soil in the furrow to smear under wet conditions varies with the design of the tine opener, with minimal disturbance openers more likely to create a smeared surface under wet conditions (Baker 2007c, 2007a). Where there is more soil disturbance, smearing of furrow walls is reduced and crop establishment improved (Iqbal et al. 1998).

The response of soil strength to a smeared furrow wall and soil drying needs to be examined with the tillage options available for mechanised row-sowing in Bangladesh. There are multiple approaches to such investigations, from direct measurement of soil strength using micro-penetrometers, to indirect methods such as computed tomography (CT) scanning of columns of soil, infiltration of dyes to indicate porosity, air-permeability measurements, and mini-rhizotron for destructive sampling of root growth directly around and through the furrow (Iqbal et al. 1998; Munkholm et al. 2003; Munkholm et al. 2008). An approach to determining if the tillage techniques are leading to limiting conditions for early crop establishment may be to sample early seedling growth at short time intervals after emergence, with a focus on root elongation, root anatomy and perhaps root biochemistry (Bengough 2003). In general, with greater soil disturbance, soil strength decreases, air-permeability increases, and shoot and root growth increases (Iqbal et al. 1998; Munkholm et al. 2008). Where smearing of furrow walls occurs, roots have a tendency to grow parallel to the smeared surface and with less soil disturbance root development was decreased (Iqbal et al. 1998; Muñoz-Romero et al. 2012). In circumstances where seedling roots penetrate into a zone of low soil strength after growing through a zone of higher soil strength, root elongation can continue to be limited for a short duration thereafter (Bengough and Young 1993). The only observations of root growth completed in this thesis
were between the SPST-sown chickpea and ST-sown chickpea in 2008 (Chapter 5). The visual differences in early crop growth and measured root growth parameters (0-15 cm depth) at flowering indicate the SPST provided a better seed-bed for crop establishment. The SPST seed-bed exhibited good soil coverage of the seed, while the ST provided poor soil coverage of the seed with some smearing of furrow walls.

Seed germination and the success of crop establishment are determined by soil physical properties in the seed-bed at sowing; namely, soil strength, soil aeration, soil water, and soil temperature. Within the seed-bed these soil physical properties are influenced by the physical characteristics of the furrow after cultivation, characteristics such as furrow shape (width and depth), distribution of soil cover and aggregate size. When the combinations of soil physical properties are optimal then seed germination, crop establishment and continued root growth are not limited. Kadžienė et al. (2011) used the Least Limiting Water Range (LLWR) to quantify soil physical conditions under different tillage techniques. The LLWR combines the soil physical properties of strength, water and aeration into one parameter which determines when the soil properties will be optimum for root growth. The optimum range is defined as the soil water content at the dry end where either of wilting point or soil strength limit root growth and at the wet end where either of field capacity or aeration limit root growth (da Silva et al. 1994).

In the HBT where the surface soil tends to dry quickly after sowing of the rabi season crop, quantifying the LLWR of the soil from rice harvest to chickpea crop establishment could be developed as a tool to better define the sowing window within which soil strength, aeration and water are not limiting to seed germination and crop establishment. The parameters of limiting soil strength for root growth or soil water content for germination may vary with soil type, tillage type and plant species. In the context of this thesis, the aim would be to determine the effect of each tillage technique on the LLWR during the period of crop establishment and to calibrate it as a tool to predict when conditions are most favourable for seeding.

The field trials completed during this study show that soil physical properties in the surface soil layer (seed-bed) will be different under the different tillage types, and these properties will also vary with soil water content. Knowledge of the soil water contents at which each tillage type will provide optimum soil conditions for seeding is continually being developed. Depth of
seeding, seed-soil cover and aggregate size in the seed bed can be better controlled under minimum tillage compared to the traditional broadcast tillage system. This means that constraints such as soil smearing in the seed-bed, uncovered seed, large clods above the seed and seeds sown at the wrong depths should be less prevalent as machinery capability and operator proficiency improves. The development of the Versatile Multi-crop Planter allows any one of several tillage types to be implemented by the one planter (Haque et al. 2011; Johansen et al. 2012). Operators therefore have the option to select the tillage operation that best suits the soil physical properties in the field at the time of sowing. To take advantage of choice in tillage type, operators and scientists developing the tillage implements need to devise simple field procedures or measurements that characterise the surface soil water, texture, and structure to identify the most suitable tillage type for the conditions of the day in that field to achieve optimum crop establishment. There are many visual soil assessment schemes which provide a semi-quantitative classification of soil condition (e.g. Ball et al. (2013)). Visual soil assessments are used to identify the structure of soil, determine limiting factors and assess the potential for soil structural degradation (Mueller et al. 2013; Murphy et al. 2013). Shepherd (2010) recommends manipulation of the soil by hand to create a rod, 7-10 mm thick by 40 mm long. After formation of the rod, if cracks form the soil is at a water content ready to cultivate. For silty soils the rod should be 10 mm thick and for clay soils it should be 7 mm thick. In the SOIL-pak guides (http://www.dpi.nsw.gov.au/agriculture/resources/soils/guides), McKenzie (2001) recommends formation of soil samples into balls and ribbons to identify the soil water content of soil and make recommendation on timing of tillage operations. This method accounts for the different behaviours of sand, silt and clay when remoulded at different water contents and relates the behaviour to the plastic limits of the soil (Campbell 1991). The recommendation for cultivation is then made depending on: (i) the soil water content, (ii) the consistency of the soil under remoulding; dry friable soil, soil which can be remoulded (plastic limit) or soil which is too wet to be remoulded (liquid limit), and (iii) the soil texture. A clay soil is recommended to be sown when dry and friable, while a soil with more sand is recommended to be sown at a soil water content close to the the plastic limit where remoulding will generally occur. This assessment which is simple, quick and field-based could be tested in
Bangladesh for use before sowing using the different tillage techniques. Operators currently using the tillage equipment have gained substantial knowledge of the soil conditions at sowing, which in combination with a visual assessment technique should improve seed-bed conditions at sowing due to informed choice of tillage type. Farmers, agronomists and machinery operators in the HBT already make decisions about field-readiness for sowing for traditional broadcast cultivation based on knowledge of soil texture and soil behaviour on remoulding. There would be merit in documenting such field-based techniques currently used by farmers in the region and together with current machinery operators, agronomists, farmers and developers of the tillage machinery creating a simple assessment technique which would differentiate among the new mechanised row-sowing techniques.

Much of the work completed in this thesis was based on the assertion in previous research that the drying seed-bed after harvest of the previous rice crop was an impediment to chickpea crop establishment in the rabi season in the HBT of Bangladesh (Musa et al. 2001). The present study determined that with mechanised row-sowing the soil physical conditions in the seed-bed are not limiting to crop establishment within quite a large sowing window (22 November to 22 December). When considering grain yield, the recommended sowing window for chickpea was refined to between 30 November and 10 December. The cut-off date for chickpea sowing in the HBT of early December does agree with recommendations by Johansen et al. (2008b). However, the 30 November starting date was late when compared to Johansen et al. (2008b). Johansen et al. (2008b) concluded that potential yields of 1000 kg/ha and greater are obtained from mid-November sowing. In this thesis the recommended start of sowing was deduced from the higher grain yields of the 2007 to 2009 sowing date trials. However, other abiotic factors apart from soil seedbed conditions affect early crop growth, vegetative growth and reproductive growth and these factors are probably better reflected in the larger number of seasons considered by Johansen et al. (2008b). Across the different seasons and sowing dates studied in this thesis, the chickpea crop responded to low or high temperature stress through modification of the flowering date and duration of vegetative and reproductive growth. This in turn affected grain yield. The significance of temperature stress in chickpea crop growth is considered below.
6.4 Implications of temperature stress

Many authors have investigated temperature limitations for chickpea growth in field and controlled environment studies (see Sections 1.3.5 and 4.4.5). Those studies largely informed the present study as to when temperature limited crop production in the field in Bangladesh. Specifically in this thesis the minimum temperature of $<15 \, ^\circ C$ was used as the limiting temperature below which vegetative growth, flower production and pod set may be affected based on Saxena and Johansen (1988), Clarke and Siddique (2004) and Kumar et al. (2010). Maximum temperature of $35 \, ^\circ C$ was used as the limiting high temperature which was based on the work of Summerfield et al. (1984) and Wang et al. (2006) who found that prolonged periods at $35 \, ^\circ C$ (day) decreased pod number and seed yields. The recent review by Devasirvatham et al. (2012) concluded that temperatures of $\geq 35 \, ^\circ C$ limit germination, $\geq 27 \, ^\circ C$ limits seedling growth, and $\geq 30 \, ^\circ C$ limits flowering and pod development.

From the field experiment results in this study, it was inferred that periods of high or low temperature limited chickpea growth in the HBT. The apparent role of daily temperatures in chickpea growth were:

1. vegetative growth stage was lengthened where the chickpea crops were at minimum temperatures less than $15 \, ^\circ C$ for prolonged periods during vegetative growth (Chapter 4, 2009);
2. grain yield was depressed due to more unfilled pods and the duration of this growth stage was decreased where maximum temperatures were greater than $35 \, ^\circ C$ for a significant period during reproductive growth (Chapter 5, 2009);
3. lower grain yields possibly from loss of flowers and limited pod production if the chickpea plants encountered lower minimum temperatures ($13$ to $15 \, ^\circ C$) during reproductive growth from flowering and during early podding (Chapter 4, 2008);
4. days to reach $50 \%$ flowering and $50 \%$ podding were increased if the chickpea crops were sown very late, due to lower mean temperatures (both maximum and minimum) from sowing to podding. The later sown crops also experienced higher mean temperatures during reproductive growth which decreased the duration of the growth stage and led to more unfilled pods and lower grain yields.
The interaction of sowing date with temperature regimes later in the growing season requires further investigation. Across all sowing dates, low temperatures were encountered for varied periods during any growth stage from sowing through to podding, but the effect on grain yield depends on the particular growth stage that was affected and the duration of low temperatures. Decreased grain yields in early sown crops in 2008 were attributed to the effects of minimum temperatures during flowering and pod development, whilst very late sown crops in 2008 and 2009 showed evidence of both low temperatures early in the season (restricting early crop vigour and vegetative growth duration) and high temperatures later in the season (unfilled pods and reproductive growth duration). The effects of both low and high temperatures on chickpea phenology, flowering and dry matter accumulation in the HBT needs further definition. Relationships could be explored through trials that closely monitor weather and micro-climate onsite and measure chickpea early growth, flowering and podding parameters which are directly affected by adverse temperatures. Whilst exhaustive studies of chickpea phenology and growth parameters across seasons and locations is not feasible, simple climate analyses to determine the probability of limiting temperatures during critical growth stages would be of value and could be further explored using daily weather data collected by BARC (Bangladesh Agricultural Research Council) from 32 locations across Bangladesh.

Although beyond the scope of the present study, crop simulation modelling could be used to build scenarios across locations from which to elucidate the temperature limitation to chickpea yields and provide estimates of risk to production based on variation in sowing time, location and the rainfall in the previous season. This would facilitate a regional analysis of temperature-related constraints, and may identify regions best suited to chickpea production as well as optimal sowing dates. The farmer-researcher ideotypes identified by (Johansen et al. 2008b) and outlined in Chapter 1 of this thesis may also be tested across seasons using the crop simulation approach to determine the success of a chickpea variety with traits identified by farmers and researchers as suitable across the region. Crop models which currently allow chickpea growth simulation are the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 2003) and the Agricultural Production Systems Simulator (APSIM) (Keating et al. 2003). Researchers have successfully used APSIM to model wheat, chickpea,
mungbean and rice for conditions in South Asia (Chauhan et al. 2008; Carberry et al. 2011; Dalgliesh and Poulton 2011; Gaydon et al. 2012). Another model has been developed for chickpea (SSM-Chickpea) and applied across a range of environments in Iran and India (Soltani et al. 1999; Soltani and Sinclair 2011; Vadez et al. 2012). All models require inputs of daily weather data, soil physical and chemical data and information on crop management and phenology. Daily weather data is available across Bangladesh and the data collected in this thesis on soil physical properties, crop management and crop phenology could be used to parameterise a model whilst trial results from 2007 to 2009 may be used to calibrate and validate the chickpea model for the HBT of Bangladesh.

The effect of high temperatures on chickpea reproductive growth especially after later sowing has possible ramifications for chickpea given climate change scenarios predicted for Bangladesh and South Asia. The mean annual temperature (and monthly temperatures) has been projected to increase by 0.8 °C by 2030 across Bangladesh and South Asia; among a range of climate models, the increase is projected to be between 0.4-1.4 °C (Preston et al. 2006; Yu et al. 2010). By 2100, the prediction is that temperature will increase over Bangladesh and South Asia by 2.6-4.6 °C. Under these conditions crop simulations showed that yield reductions for rice could be up to 8 % and for wheat by 32 % (Mallick and Rahman 2010; Lal 2011). In Bangladesh in the 2030s, increasing or decreasing trends in rainfall are predicted to occur depending on the month or season, while by the 2050s annual precipitation is predicted to increase by 4 % (Yu et al. 2010). The December to February quarter, which is relevant to chickpea, is projected to have 0-16 % decline in rainfall in South Asia, with increases in precipitation occurring from March to November, during the summer monsoon period (Cruz et al. 2007; Yu et al. 2010; Lal 2011). The decrease in precipitation over the rabi season is of small magnitude, since it occurs in the driest period of the year. However, the combination of low rainfall or no rainfall in this season together with increased temperatures will increase the likelihood and intensity of drought conditions (Selvaraju et al. 2006; Yu et al. 2010; Lal 2011). In the present study decreases in chickpea yield were attributed not only to high temperatures but to the number of successive days of exposure by plants to those higher temperatures. Chickpea yield declined when a significant proportion of the chickpea reproductive phase was
spent at maximum temperatures greater than 35 °C. This was equivalent to an increase in maximum temperatures of 3.7 °C, when compared to the reproductive growth of a crop not affected by high temperatures. The review by Devasirvatham et al. (2012) highlighted the effect high temperatures (>30 °C) and duration of exposure can have on all the growth phases of chickpea.

6.5 Conclusion

The cultivation of chickpea and other grain legumes in the HBT provides farmers with an alternative land use to leaving the land fallow during the rabi season. Such crops provide additional income and improve household food security. The development of mechanised one-pass row-sowing improves the reliability of crop establishment of the crop following rice harvest as the seed-bed is more likely to remain at soil water contents optimum for crop establishment than would be the case with traditional broadcast cultivation techniques. In addition the range of tillage techniques made available with planters such as the VMP, means that cultivation can occur across a range of soil types and soil water contents. Decisions about tillage type and the soil water content at sowing will determine if soil physical properties in the seed-bed directly after sowing will limit chickpea germination and emergence. The move to mechanised one-pass row-sowing can allow early sowing of the chickpea crop, which in current weather conditions means the reproductive phase of growth is more likely to be within non-limiting temperature conditions. Early sowing can allow seedling growth and biomass formation before the cold temperatures whereas December sowing can increase the probability of low temperature constraints during vegetative crop growth.

The investigation of plant row spacing and PPD in south-west WA showed that row spacing can alter the uptake of soil water during the season, with chickpea plants at narrow row spacing using more soil water early in the season than plants at wider row spacing. When pre-season irrigation was added the chickpea plants utilised the additional water early in the season, but any advantage of this additional rainfall was lost by the reproductive growth stage. The investigation of row spacing and pre-season irrigation provides insight into potential outcomes of row spacing and PPD investigations with chickpea in the HBT. Widening the row spacing of
chickpea plants in the HBT may allow plants to access soil water when required for reproductive growth both vertically and horizontally in the soil profile as the season progresses. However, with the low rainfall in the season and high temperatures the evaporation from bare soil between rows may accelerate water loss before plant roots reach the inter-row space. Further investigations into modifying PPD and row spacing with sowing by the VMP will determine the scope for varying PPD and row spacing to improve water use efficiency of chickpea in the HBT.
7 Reference


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