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Optimum Soil Water Content for Chickpea Emergence in Heavy-Textured Soils of North-West Bangladesh

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Abstract

Sowing of chickpea in the heavy-textured soils of north-west Bangladesh with minimum tillage technology aims to increase the timely planting of large areas during a relatively short sowing window before soil water deficit limits germination and emergence. However, the seedbed conditions into which chickpea is sown need to be better quantified, so that limiting factors which affect germination and emergence can be identified. Two of the soil physical characteristics of importance are soil water and aeration. Growth cabinet studies have identified the fastest germination and emergence of chickpea on representative soils for this area at gravimetric water contents of 17–18 %, whilst soil water contents above and below this delayed germination and emergence. Emergence was recorded at soil water potentials between field capacity (–10 kPa) and wilting point (–1500 kPa). Emergence was possible at lower soil water potentials in the finer textured soil, whilst in coarser textured soil, emergence was still possible at higher soil water potentials.

Introduction

Chickpea (*Cicer arietinum* L.) crops in rice-based 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. 2010). An area representative of this cropping system is in north-west Bangladesh, in the High Barind Tract (HBT). As in other regions of South Asia, after harvest of the rice crop, the HBT 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, Waddington et al. 2010, Li et al. 2011). This results in suboptimal 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. 2010). In addition to limiting surface soil water conditions, crop establishment can also be hampered by hard-setting soils, poor quality seed and sowing under suboptimal conditions due to scarcity of labour or delays to sowing which are common with traditional broadcast systems using animal-drawn technology (Harris et al. 2005, Johansen et al. 2008a).

The soil physical conditions determined by 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 seedbed that either promotes or limits seed germination and seedling emergence (Atkinson et al. 2007). Ten per cent 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 2007), 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 (θ_g) 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 decrease 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 72–75 % 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 ψ decreased from 0 to -750 kPa, and was not possible at -1000 kPa (Singh and Afria 1985) whilst emergence tolerated ψ only as low as -500 kPa (Sharma 1985). Even at optimum ψ for germination, decreased hydraulic conductivity and reduced seed-soil contact can impede uptake of water and delay germination (Hadas and Russo 1974, Hadas 1977).

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 seedbed properties after mechanised row-sowing to be matched to chickpea requirements. The objective of this study was to identify the soil water content and soil water potential required for emergence of plants under known soil bulk density on clay-rich soils.

Materials and Methods

Four laboratory experiments were conducted to investigate the germination and emergence of chickpea at different water contents. Two soil types were used in these laboratory experiments. One was a surface soil (0–10 cm) from Merredin, Western Australia (WA) (Australian soil classification, Calcic Red Dermosol, (Isbell 1996)). The particle size distribution was 61 % sand, 10 % silt and 29 % clay. Undisturbed soil from the field had a bulk density of 1.6 g cm^{-3} (Vance 2013). The second 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 of this soil was 48 % sand, 24 % silt, 28 % clay, and the bulk density of undisturbed soil collected from the field was 1.4 g cm^{-3} (Vance 2013). The Bangladesh soil had a similar texture and hard-setting nature to soils in the HBT and was representative of the region (Ali et al. 2005, 2007). 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 the required 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, but lower in the percentage of silt. Experiments 1 and 2 were conducted using surface soil from Merredin, and Experiments 3 and 4 using the soil from Bangladesh. Experiments 1–3 were carried out at Murdoch University, WA; Experiment 4 was completed in Rajshahi, Bangladesh.

Seeds of desi chickpea were used in all experiments. Desi type chickpeas are characterized as small coloured seed that are angular in shape (Malhotra 2007). Cultivar Genesis 836 was used in Experiments 1–3 and cultivar BARI Chola 5 in Experiment 4. Seeds were selected for uniformity of size in each experiment. At harvest, seeds were inspected to determine whether germination had occurred (radicle $>2 \text{ mm}$ 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.

Experiment 1

Experiment 1 was conducted to determine the soil water content at which chickpea germination is limited. There were five treatments of soil water content at 13 %, 14 %, 18 %, 23 % and 28 % (w/w), referred to as treatments 1, 2, 3, 4 and 5, respectively. Soil was wet-up to the treatment water contents and mixed before being left in a sealed container to equilibrate for 48 h. 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 cm^{-3} . Bulk density was calculated from the air-dry mass and volume of soil in the Petri dish. 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. Each seed was inspected to see whether germination had occurred and whether a shoot was visible.

Experiment 2

Experiment 2 was conducted to determine how soil water content affected emergence rate of the seedlings. There were eight soil water content treatments of 3 %, 10 %, 12 %, 14 %, 17 %, 23 % and 27 % (w/w) with eight replications. The driest treatment had a mean θ_g of $2.76 \% \pm 0.04$, which was the air-dry water content of the soil. 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 cm^{-3} , calculated by the mass of soil in the volume of the pot, filled to a predetermined height. However, soil water contents of 3 %, 10 %, 23 % and 27 % all settled to below this height, resulting in bulk densities of 1.6, 1.4, 1.6 and 1.8 g cm^{-3} , respectively. One seed was sown per pot at 3 cm depth. The pot was placed in a sun-bag (Sigma-Aldrich, Sydney, New South Wales, Australia) and the sealed bag placed in a growth cabinet at a constant day/night temperature of 25 °C and 12 h day/night. Sun-bags are $44 \times 20.5 \text{ cm}$, gusseted transparent bags, with a 24 mm diameter, $0.02 \text{ }\mu\text{m}$ 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 whether seedlings had emerged. Twelve days after sowing, all

remaining pots were removed and destructively sampled. Each seed was inspected to see whether germination had occurred and whether a shoot was visible.

Experiment 3 and 4

Experiments 3 and 4 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 3, carried out at Murdoch University, the six soil water content treatments were 12 %, 14 %, 16 %, 19 %, 22 % and 23 % (w/w), 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 cm^{-3} . One seed was sown per pot at 3 cm depth. The pots were placed in sun-bags and put in a growth cabinet at constant day/night temperature of 20 °C and 12 h day/night. After sowing, the pots were monitored daily to determine whether seedlings had emerged. Experiment 4 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. The experiment consisted of seven treatments of soil water content, at 2 %, 6 %, 12 %, 17 %, 20 %, 21 % and 27 % (w/w), with ten replications. 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 whether seedlings had emerged.

Soil physical properties

In each experiment, the gravimetric soil water content (θ_g) was determined for each treatment at sowing and at harvest. For both soils, 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 (θ_{fc}) and wilting point (θ_{wp}) was considered to be at the water potentials of -10 and -1500 kPa, respectively (Cresswell 2002). Gravimetric water contents were converted to volumetric water content (θ_v) using the sample bulk

density. Soil water release curves were established for each soil type using the 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 θ_v is the volumetric water content ($\text{m}^3 \text{m}^{-3}$), θ_r is the residual water content ($\text{m}^3 \text{m}^{-3}$), θ_s is the saturated water content ($\text{m}^3 \text{m}^{-3}$), ψ is the water potential (cm), and α , n and m are constants that affect the slope of the retention curve: α 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 θ_s , θ_r , α , n and m and the following equations used to calculate ψ from a given θ_v (van Genuchten et al. 1991):

$$\psi = \frac{1}{\alpha} (S_e^{-\frac{1}{m}} - 1)^{\frac{1}{n}}$$

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 % (θ_{afp}) was estimated from:

$$\theta_{afp} = \theta_s - 1$$

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

Statistical analysis

Means and standard errors of the means are presented for all data, calculated by GenStat v11.1 (VSN International Ltd, Hemel Hempstead, UK).

Results

Soil physical characteristics

One water release curve was calculated for each soil type (Merredin or Bangladesh soil) from the relevant data (Fig. 1). The parameters estimated from the RETC program were as follows: (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, $\theta_r = 0.1295 \text{ m}^3 \text{ m}^{-3}$, $\theta_s = 0.5710 \text{ m}^3 \text{ m}^{-3}$, $\alpha = 0.0265$; $n = 1.4817$.

Germination and emergence of chickpea at different water contents

In Experiment 1, the actual θ_g at sowing of the five treatments was 13 %, 14 %, 18 %, 23 % and 28 % (Table 1). At a θ_g of 18 %, germination of seeds had reached 100 %, 3 days after sowing (DAS) (Fig. 2a). With increasing θ_g from 13 % to 18 %, the time taken for germination to occur decreased. At the driest θ_g (13 %), the germination at 3 DAS was 45 % and rose to 100 % at 11 DAS. As the θ_g at sowing increased to 23 % and 28 %, the number of germinated seeds increased with DAS.

Shoot development was also related to θ_g at sowing (Fig. 2b). At $\theta_g \geq 18$ %, germinated seeds showed first signs of shoot development at 6 DAS. When θ_g at sowing increased from 18 % to 28 %, the number of seeds that had developed a shoot at 6 DAS decreased (67 down to 21 %). With increasing DAS, the numbers of seeds with shoot development increased. At the dry θ_g of 14 %, even though germination was successful (>83 %), shoots developed in 33 % or less of seeds.

Field capacity (θ_{fc}) was calculated to be 25.7 %, and wilting point (θ_{wp}) 9.9 %, therefore treatments with θ_g of 13 %, 14 %, 18 % and 23 % were between θ_{fc} and θ_{wp} at the time of sowing (Table 1).

Soil water potential and θ_g decreased from the sowing to the final sample date (12 DAS) for all treatments (Fig. 3). When the germination percentage was maximum at 3 DAS (Fig. 2a), the ψ was lower than ψ for field capacity (Fig. 3b). In the 13 % and 14 % θ_g treatments, with decreasing ψ after sowing, time to maximum germination increased to 6 and 11 DAS, respectively. In the wet soil (28 % θ_g), the ψ at sowing was greater than field capacity (Fig. 3b) and maximum germination was at 10 DAS (Fig. 2a). This could indicate that the seeds exposed to drier ψ than -99 kPa (ψ at 14 % θ_g ,

Table 1) require more time to absorb water needed to germinate, whilst the seeds exposed to wetter than ψ of -13 kPa (ψ at 23 % θ_g , Table 1) may have been limited by aeration, requiring the soil to dry somewhat before germination could occur.

Experiments 2–4 were conducted to determine the time taken for the chickpea to emerge over a range of θ_g at sowing. In Experiment 2, conducted with the Merredin soil, θ_g at sowing covered the range 3–27 %. 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)).

Emergence did not start in any treatment until 4 DAS, and no further emergence occurred after 8 DAS (Fig. 4). At 12 DAS, all remaining pots were harvested. At θ_g of 3 %, 8 %, 10 % and 27 %, no seeds emerged over the duration of the experiment: these corresponded to ψ values dryer than wilting point and wetter than field capacity, respectively. In treatments with 12 %, 14 % and 17 % θ_g at sowing, all seedlings emerged. The 17 % θ_g had the fastest rate of emergence, with emergence of all seedlings complete by 5 DAS. Chickpea seeds sown into drier θ_g had delayed emergence, taking until 4–6 DAS at a θ_g of 14 % and 5–8 DAS at a θ_g of 12 %. The 23 % θ_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 (Figs 2a and 3b), as the θ_g approaches field capacity (-13 kPa at 23 % θ_g), emergence also was delayed, with the fastest rate of emergence at -34 kPa (17 % θ_g), and 100 % emergence reached at ψ as low as -220 kPa (12 % θ_g) (Fig 4).

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 % θ_g were viable seed, whilst five-eighths of the seeds from the 23 % and 27 % θ_g became mouldy.

A preliminary experiment of the emergence of seeds in HBT soil was conducted in the growth cabinet at Murdoch University (Experiment 3). In the HBT soil, the values of θ_g at sowing were from 12 % to 23 %. No plants emerged at the θ_g of 12 %. The θ_g of 19 % had the fastest rate of emergence, although only 75 % of seeds emerged 5 DAS with no further seeds emerging after that time (Fig. 5). The rates of emergence of chickpea sown at θ_g of 16 % and 22 % were similar, with 100 % of

emergence reached 9 DAS in the 22 % θ_g . The drier and wetter treatments of 14 % and 23 % θ_g , respectively, had delayed emergence and did not reach 100 % emergence.

Pot size for the Murdoch University growth cabinet study (Experiment 3) was small and θ_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 θ_g and have pots which allowed greater soil volume for root growth, a second emergence experiment was conducted in Rajshahi, Bangladesh (Experiment 4). Soil water contents at sowing ranged from 2 % to 27 %. No seeds emerged at $\theta_g < 12\%$ or $> 21\%$ (Fig. 6). The 17 % θ_g had the greatest rate of emergence at 4 DAS and reached 90 % emergence at 6 DAS. Shoots in the 20 % and 21 % θ_g treatments also started emerging 4 DAS, and 90–100 % emergence was reached 5–7 DAS. The 12 % θ_g had delayed emergence, 6 DAS, but did reach 100 % at 7 DAS.

Of the seeds that did not emerge in all the experiments conducted in HBT soil, those seeds sown at θ_g of 12 % in the smaller pots (Experiment 3) had 75 % germination although none emerged by day 10 (possibly due to soil drying out in pot). At the wetter $\theta_g > 23\%$, if the seeds did not emerge, it was because they did not germinate.

The highest rate of emergence in the Bangladesh soil was at soil water potentials of -81 to -139 kPa (17–19 % θ_g), but emergence was delayed by drying soil to -274 to -538 kPa (12–14 % θ_g), and in wetter soil at -56 kPa (23 % θ_g). No emergence occurred at soil water contents which correlated with soil water potentials drier than -538 kPa or wetter than -56 kPa.

Discussion

Soil water and soil aeration

The Merredin and HBT soil types, despite differences in particle size distribution, exhibited similar behaviour in the emergence characteristics of chickpea under different soil water contents. The rate of germination and emergence of seeds was fastest in both soils when initial θ_g at sowing was between 17 % and 18 %. At the drier θ_g of 10 %, germination did not occur and at 12 %, emergence was

delayed. In wet conditions, above 23 % θ_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 were reported to occur with θ_g from 9 % to 34 %, whilst emergence declined with soil drying (Fig. 7; Saxena et al. 1983, Sharma 1985, Johansen et al. 1997, Hosseini et al. 2009a). The present results suggest that for a more specific soil texture range, a narrower range of optimal soil water contents are required for optimal germination and emergence. Moreover, the present results highlight the harmful effects of excess soil water for germination and emergence of chickpea as well as dryness.

A closer examination of chickpea emergence results from previous studies can explain the apparent discrepancy with the present results (Fig. 7). In particular: (i) previous studies had not reported an upper limit of θ_g above which soil water limits emergence and (ii) that the range of θ_g over which chickpea reached 80–100 % emergence was quite wide. When the relationship between ψ and emergence was compared for the available data (Fig. 7b) for three soils (Merredin soil, Bangladesh soil and silty clay-textured soil reported by Sharma (1985)), ψ was comparable where the emergence was highest (80–100 %), even though the associated θ_g was quite different (Fig. 7a). The studies where θ_{fc} were lower (25 % and 19 %) have a lower range in θ_g over which optimum emergence occurred (present study and Hosseini et al. 2009b). Where θ_{fc} was higher, such as in Sharma (1985) and Saxena et al. (1983) who reported θ_{fc} was 34 % and 32 %, respectively, optimum emergence occurs at a higher range of θ_g .

The water release curves of the Merredin and Bangladesh soils were different (Fig. 1) with the θ_{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 θ_{wp} (–1500 kPa) of the Merredin soil was only higher by 2 %. This means that at optimum rates of chickpea germination and emergence, each soil type had slightly different ψ . In wet soil, 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 ψ decreased, emergence was delayed but was still possible up to -220 kPa in Merredin soil and -583 kPa in Bangladesh soil. Hence, the present results indicate that the ψ 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 ψ (drier limit) in Bangladesh soil than in Merredin soil, whilst chickpea in the Merredin soil was able to emerge at higher ψ (wetter limit) (Fig. 7b). The differences in ψ 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). Such 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 ψ than in coarse-textured soils, but coarser textured soils enable germination at higher maximum ψ (Collis-George and Sands 1959, Dasberg and Mendel 1971). The Merredin soil with 61 % sand and 29 % clay had 17.7 % θ_g at -33 kPa, the Bangladesh soil with 42 % sand and 28 % clay had 27 % θ_g at -33 kPa whilst a clay soil (Sharma 1985) with 12 % sand and 58 % clay had 34 % θ_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). Water content (θ_{afp}) at 10 % air-filled porosity was estimated to be 25–20 %, in the Merredin soil and 30–25 % 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 <10 % air-filled porosity in Merredin soil but in the Bangladesh soil was equivalent to 15 % air-filled porosity. 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 average for 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. Whilst emergence was delayed by low soil water, it still reached 90 and 100 %, a similar success rate to the moderately wet soils (θ_g , 14–21 %) (Figs 4, 5 and 6). 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 (Fig. 3). However, in the greater volume of soil used in the emergence trial (Fig. 4), the wet soil treatments (θ_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 suggest that few seeds will germinate and emerge on poorly structured 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.

In a parallel field study in the HBT by Vance et al. (2014), it was found that within the range of sowing dates from 22 November to 22 December, θ_g remained between 12 % and 24 % (w/w). The seeds were sown in one pass using mechanised row-sowing. Limiting soil water conditions due to drying in the seedbed occurred after final emergence. Whilst the soil water content remained at values that did not limit chickpea establishment in the field within the period from 22 November to 22 December, early or late sown crops can be affected by periods of low or high temperature during the growing season, which may affect vegetative or reproductive growth and decrease final yields. Hence, across a number of studies in Bangladesh chickpea grain yields have been found to either peak with November sowing, maintain high yield with early December sowing and/or decline with sowing dates into late December (Musa et al. 2001, Johansen et al. 2008b, Kabir et al. 2009, Ahmed et al. 2011, Vance et al. 2014). The grain yield of the crop will be determined by the combination of sowing date, crop establishment, agronomic management, soil water and climatic conditions (Johansen et al. 2008b, Vance et al. 2014).

Shoot development

In addition to germination assessment, the development of shoots was also assessed 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 θ_g from the 18–23 % recorded at 6 DAS. When the θ_g was outside of this range, the first evidence of shoot development was reported in only 21 % of the seeds in the wet soil (-6 kPa ψ) at 6 DAS, and 33 % of the seeds in the dry soil

(-99 kPa ψ) at 10 DAS. 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 ψ 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 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 (*Vigna radiata* L. R. Wilczek), 50 % germination was reported at ψ of -1700 kPa, and 50 % emergence was reported at ψ 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.

Conclusion

The rate of germination and emergence of chickpea seeds was fastest in silty clay soils which had θ_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 ψ in the finer textured Bangladesh soil and at higher ψ in the slightly coarser textured Merredin soil type. The differing ranges in optimum ψ of each soil type for chickpea emergence may reflect the different soil particle and pore size distributions that 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 were limited with <10 % air-filled porosity due to insufficient oxygen supply. The air-filled porosity where emergence was limited in wet soil 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.

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Figure 1. Fitted water release curve for the Merredin soil (---) and the Bangladesh soil (—). The soil water potentials (ψ) corresponding to field capacity (–10 kPa, — FC) and wilting point (–1500 kPa, — WP) 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.

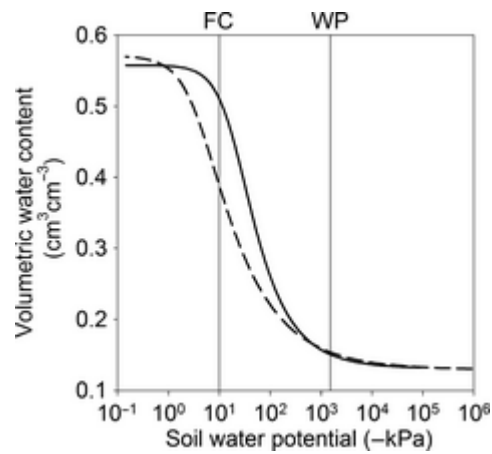


Figure 2. The germination and shoot production characteristics of chickpea seeds sown at water contents ranging from 13 % to 28 % (w/w) in a Merredin sandy clay loam for Experiment 1. (a) Percentage germination of chickpea seeds 3–12 days after sowing (DAS). (b) The percentage of seeds which had a visible shoot at 3–12 days after sowing (DAS). Error bars indicate 1 standard error of the mean where visible.

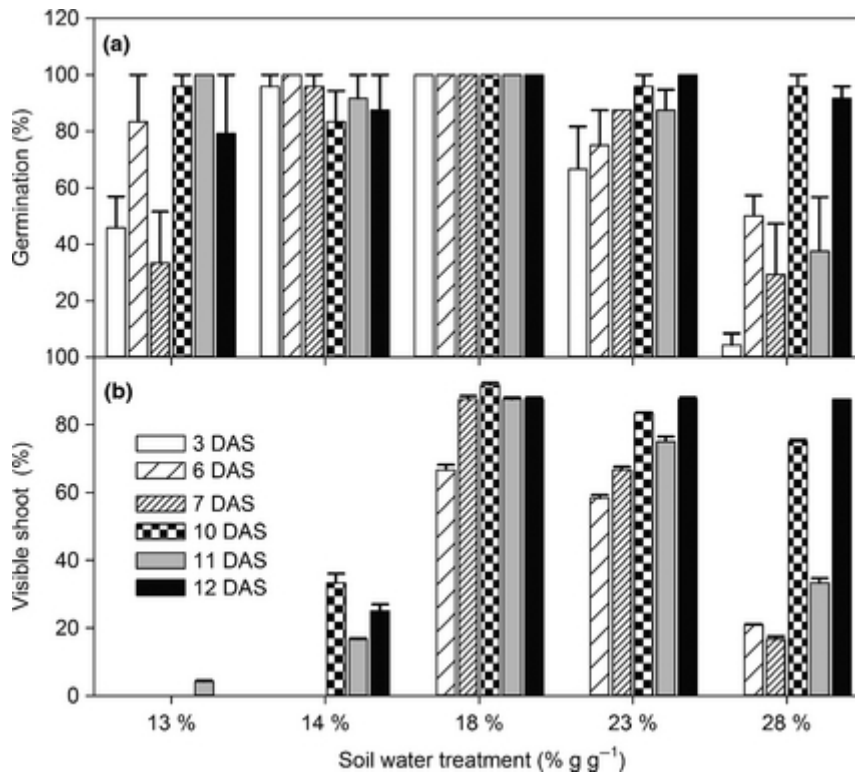


Figure 4. Rate of emergence of chickpea seeds sown into the Merredin sandy clay loam at gravimetric soil water contents (θ_g) ranging from 12 % to 23 % (w/w) in Experiment 2. Note that no seedlings emerged at the θ_g of 3–10 and 27 %. Eight replicates were sown for each treatment.

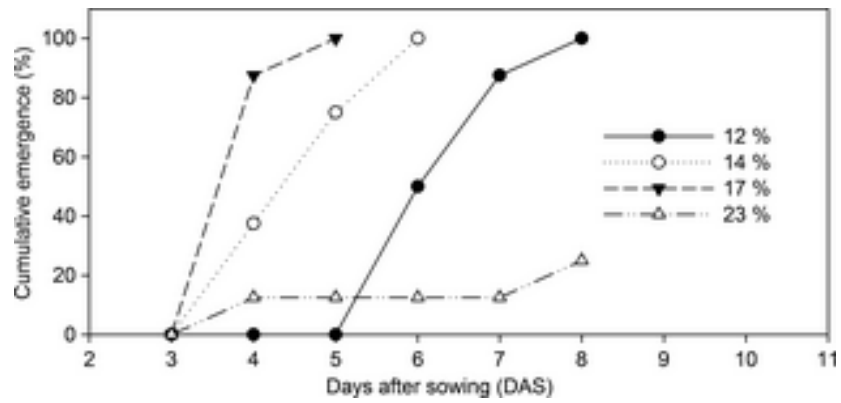


Figure 5. Rate of emergence of chickpea seeds sown into soil from the High Barind Tract of Bangladesh at gravimetric soil water contents (θ_g) ranging from 14 % to 23 % (w/w) from Experiment 3. No seedlings emerged at the θ_g of 12 %. Eight replicates were sown for each treatment.

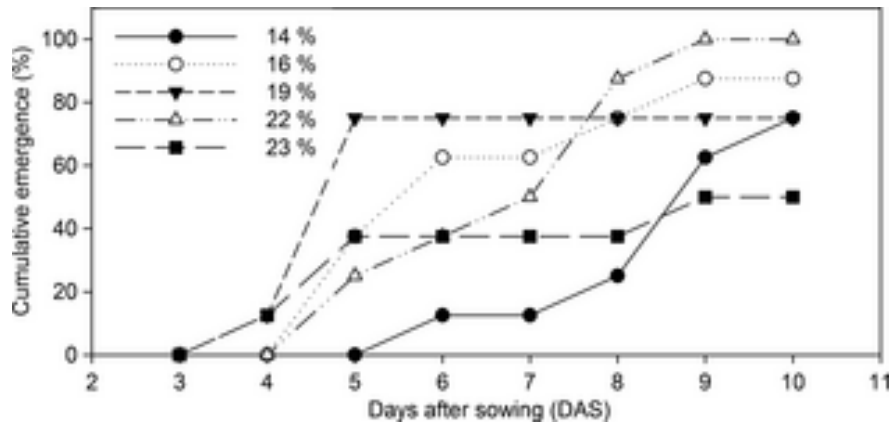


Figure 6. Rate of emergence of chickpea seeds sown into High Barind Tract soil of Bangladesh (Experiment 4) at gravimetric water contents (θ_g) ranging from 12 % to 27 % (w/w). No seedlings emerged at $\theta_g < 12\%$ or $> 21\%$. Ten replicates were sown for each treatment.

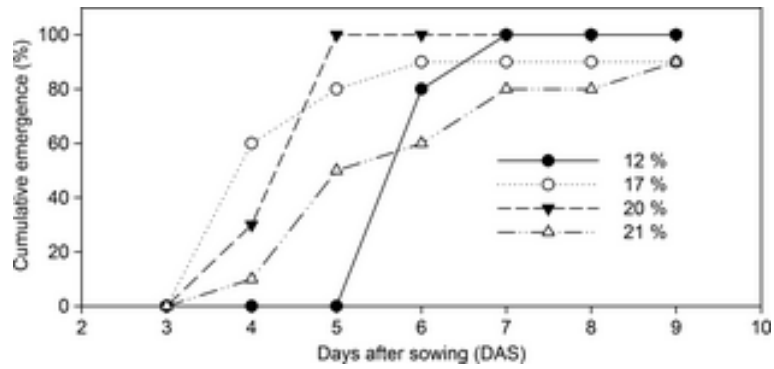


Figure 7. The percentage emergence of chickpea seedlings with (a) different soil water content and (b) soil water potential across different studies in Western Australia (present study and Hosseini et al. (2009b)), Bangladesh (present study) and India (Saxena et al. 1983, Sharma 1985).

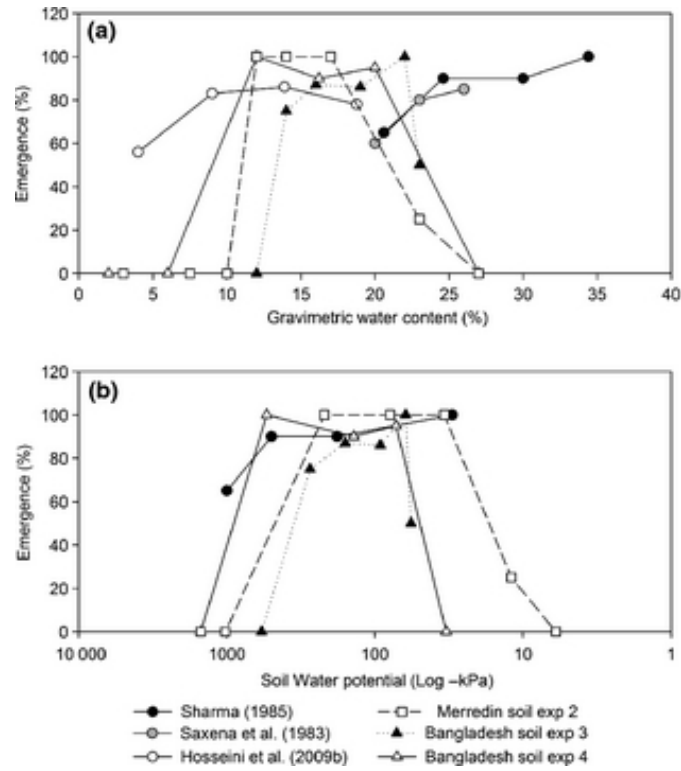


Table 1. The mean gravimetric soil water content (θ_g , %) of each treatment at sowing in Experiment 1. Values are means of three replicates. The θ_g at field capacity (θ_{fc} , -10 kPa) and wilting point (θ_{wp} , -1500 kPa) were determined experimentally, whilst the soil water potentials (ψ , kPa) for each soil water treatment were calculated from the water release curve (Fig. 1)

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