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Identifying chickpea homoclimes using the APSIM chickpea model

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Abstract. Chickpea (*Cicer arietinum* L.) has been traditionally grown in India but is a relatively new export crop in Australia where its cultivation is expanding into new areas. The objective of this study was to identify homoclimes (i.e. similar chickpea-growing environments) in the major chickpea-growing areas of the 2 countries, using the Agricultural Production Systems Simulator (APSIM) chickpea model. The model, which processes climatic, soil, and plant information on a daily time step, was first validated and then used to simulate flowering, maturity, and grain yield of Amethyst, a mid-season cultivar, and Barwon, a full-season cultivar, on low (100 mm), medium (150 mm), and high (190 mm) water-holding capacity soils, using historical climatic data of 67 Australian and 24 Indian locations. The mean of annual outputs of flowering, maturity, and grain yield of the 2 cultivars on 3 soils was then clustered using Ward's hierarchical complete linkage clustering procedure. At a 90% level of similarity, all the locations could be grouped into 6 homoclime clusters. The Australian locations appeared more diverse as they were present in all the clusters, whereas the Indian locations were present only in clusters 1, 2, and 6. While there were clear geographical patterns of spread of these clusters, in Australia they were not entirely related to latitude. The cluster 1 and 2 locations, which represent the largest chickpea-growing area in Australia, had homoclime locations in common with northern India. The clustering of locations appeared generally consistent with the known adaptation of chickpea in different environments of the 2 countries and therefore suggests that the methodology could be potentially used for complementing conventional approaches of introducing or exchanging germplasm, as well as determining appropriateness of breeding/testing sites.

Introduction

Chickpea (*Cicer arietinum* L.) is a cool-season food legume, which is grown in Africa, West Asia, South Asia, and Europe. Its cultivation has recently expanded into non-traditional areas of North America and Australasia. As average grain yields of chickpea are generally <1 t/ha, growers, especially in new regions, are always seeking to adopt higher yielding and better adapted cultivars either bred locally or introduced from other national and international breeding programs or seed companies to improve their gross margins.

In chickpea, large genotype × environment (G × E) interactions for seed yield have been recently reported (Berger *et al*. 2004, 2006) and an apparent association between germplasm origin and specific adaptation has also been uncovered (Berger *et al*. 2006). Such interactions make it difficult to make recommendations for new areas without conducting elaborate variety evaluation trials over several sites and seasons. However, conducting such large multi-location trials may not always be feasible due to logistical and other reasons. It would therefore be appropriate to complement current varietal testing approaches with other methods, such as identification of homoclimes (similar climatic environments), that could hasten the introduction of high-yielding cultivars into new areas. The homoclime analysis approach has previously been applied to determine adaptation ranges of perennial crops or trees, which can take many years to establish (Russell and Moore 1976; Booth *et al*. 1987; Smart 2003). It has also been used to identify climatic adaptation ranges of various pasture legume species (Russell and Webb 1976), as well as to examine the potential for invasion of annual weed species (Holt and Boose 2000).

An underlying assumption in the homoclime approach is that the potential for expression on adaptive plant traits of a given cultivar will be similar within a homoclime and hence its performance. Indeed, Malhotra and Singh (1991) reported that genotype × environment interaction was minimal within a cluster formed using flowering and grain yield data of 2 international chickpea trials. Limited work conducted to describe the West Asia North Africa (WANA) chickpea region in terms of its climatic profile and nature of stresses experienced by the crop (Saxena *et al*. 1996) suggested that this approach, if applied on a wider scale, can lead to a better understanding of adaptation ranges in this crop as well. This was further supported by a recent eco-graphic analysis of chickpea by Berger and Turner (2007) which showed that chickpea is grown in a wide range of habitats characterised by different climates that exert different selection pressures on the crop.

Two critical issues relevant to using the homoclime approach in chickpea are the definition and development of appropriate tools to identify homoclimes. Traditional homoclime approaches have often used physical variables to classify environments, and generally have ignored their effects on plant responses and hence may not be crop specific. To capture the crop specificity in a better way it would, however, be ideal if environments were characterised based on the crop's response to environments. For example, environmental factors such as temperature, photoperiod and seasonal rainfall can have significant effects on crop phenology and yield. Defining a

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homoclime only in terms of rainfall or temperature averages using pattern analysis may be less informative than defining it in terms of stresses resulting from these climatic variables, and also mechanisms the crop uses to cope with these stresses.

Drought and cold stress are the two major abiotic stress factors that have been identified to affect chickpea adaptation in different regions (Berger and Turner 2007). The crop's ability to tolerate these stresses in part is conferred via its phenology which is a cultivar specific characteristic (Berger *et al.* 2004, 2006) modulated by temperature and photoperiod (Roberts *et al.* 1985). Chickpea phenology is also affected by low temperature (<15°C) and drought stress (Singh 1991; Clarke and Siddique 2004). For chickpea a homoclime, for example, could be a group of environments creating a similar degree of drought or cold stress, as well as modulation of phenology to cope with these stresses. There could be substantial application of this type of homoclime approach if it could characterise environments in such a way.

In the past, flowering and grain yield data recorded in yield trials have been used to characterise chickpea environments with some success (Malhotra and Singh 1991). A new approach for this purpose could be to generate such data using a simulation modelling framework. The Agricultural Production Systems Simulator (APSIM) developed in Australia is one such modelling framework that has the ability process climatic, plant and soil information (McCown *et al.* 1996). The model been successfully used to characterise sorghum (*Sorghum bicolour* L.) drought environments (Chapman *et al.* 2002), and is being applied to decipher gene-to-phenotype relationships in order to improve plant breeding strategies (Chapman *et al.* 2003). The model can also simulate chickpea growth and grain yield (Robertson *et al.* 2002). It has, however, not been applied to identify chickpea homoclimes.

The objective of this study was to explore if the APSIM chickpea model could be used to identify homoclimes, using locations in Australia where chickpea is a relatively new crop and covers a range of the temperate, sub-tropical and tropical environments, and in India where the crop has been grown for a long time in subtropical and tropical environments. In addition, historical daily climatic and validation datasets for the chickpea model were available for many locations of both countries.

Materials and methods

This study involved two stages; firstly to validate the APSIM chickpea model across a range of locations in Australia included in the homoclime analysis; and secondly to apply this model to generate outputs for several locations in Australia and India to identify chickpea homoclimes in both the countries.

Model validation

All simulations were conducted using the APSIM chickpea module (version 4) (Robertson *et al.* 2002) incorporating the chickpea model. As the APSIM chickpea model has been designed to simulate a uniform block of land and does not account for the confounding factors of pests, diseases and variable crop stands, its outputs represent the situations free from these confounding factors. The model simulates crop development, growth, and grain yield in response to inputs of radiation, ambient temperature, soil water, and nitrogen supply on a daily time step. The model was calibrated using data collected in central and south-east Queensland, and New South Wales, and has not been widely applied to winter sowings in Mediterranean type environments of Southern Australia, and to autumn sowings which typify Indian production systems. In the Mediterranean type environments of Australia and northern Indian environments, post-anthesis temperature of <15°C inhibits podset (Srinivasan *et al.* 1998; Berger *et al.* 2004). This essentially means an increase in thermal time target for the crop during the reproductive period. As cultivar parameters in the original model did not have the ability to account for this effect, a modification in cultivar parameters in the model was considered necessary to account for the period during which pod set and filling will not occur (or will occur over a longer period), due to temperatures/photoperiods being unfavourable for podset. This modification increases the thermal time target for periods between flower initiation and flowering, and between flowering and grain-filling under progressively shorter days to account for periods of low temperatures/photoperiods inhibiting pod filling, and has been calibrated against the observed data.

For model validation, data on time to flowering, maturity and grain yield from three trials conducted throughout Australia were used, including studies by Thomas and Fukai (1995), Berger *et al.* (2004) and McCosker and Douglas (unpublished data). These trials covered sites at Emerald (23°31′S and 148°10′E), Biloela (24°8′S and 150°20′E), Roma (26°34′S and 148°47′E), Redland Bay (27°37′S and 153°19′E), Billa Billa (28°12′S and 150°21′E), Warwick (28°13′S and 152°6′E) in Queensland, Tamworth (31°5′S and 150°50′E) in New South Wales, Merredin (31°48′S and 118°16′E) in Western Australia, Minnipa (32°50′S and 135°10′E) in South Australia, and Walpeup (35°7′S and 142°E) in Victoria (Fig. 1). The agronomic details used for simulation are given in Table 1. These trials were conducted either under completely rainfed (Berger *et al.* 2004) conditions, or with full irrigation (Thomas and Fukai 1995), or irrigation was only given to establish a crop (C. Douglas, QDPI&F, pers. comm.). Soil depth data gathered from the literature was specified in the soil parameter file and starting soil water was set at 90 days before sowing to allow

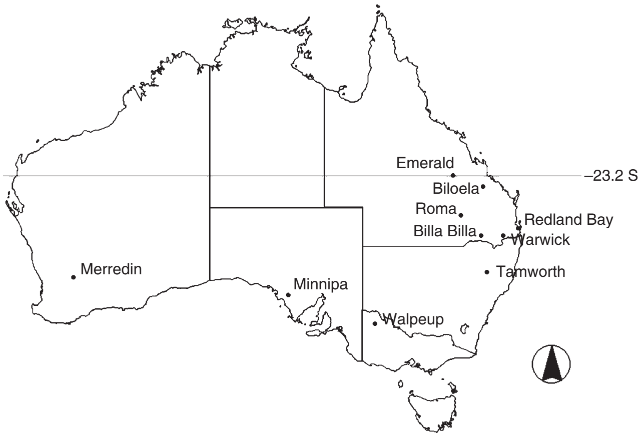


Fig. 1. Australian locations used in validating the APSIM chickpea model.

Table 1. Agronomic details used for validation of the APSIM chickpea model at different locations

Location	Date of sowing	Cultivar	Plants/m^2	PAWC (mm)	Starting water	Water status	Reference
Billa Billa	20/05/2003	Amethyst	30	190	2/3rd	R	A
Billa Billa	1/06/2004	Amethyst	30	190	Full	R	A
Biloela	26/05/2003	Amethyst	28	240	Full	R	A
Biloela	26/05/2004	Amethyst	30	240	Full	R*	A
Emerald	20/05/2003	Amethyst	34	150	Full	R*	A
Emerald	21/05/2004	Amethyst	17	150	Full	R*	A
Warwick	3/06/2003	Amethyst	30	240	2/3rd	R	A
Warwick	7/06/2004	Amethyst	30	240	2/3rd	R	A
Roma	14/05/2003	Amethyst	30	190	Full	R	A
Roma	19/05/2004	Amethyst	30	190	2/3rd	R	A
Merredin	8/06/1999	Amethyst	53	190	Full	R	B
Merredin	8/06/1999	Barwon	53	190	Full	R	B
Merredin	16/06/2000	Amethyst	28	190	Full	R	B
Merredin	16/06/2000	Barwon	28	190	Full	R	B
Minnepa	1/06/1999	Amethyst	45	190	1/3rd	R	B
Minnepa	1/06/1999	Barwon	45	190	1/3rd	R	B
Minnepa	5/06/2000	Amethyst	41	190	1/3rd	R	B
Minnepa	5/06/2000	Barwon	41	190	1/3rd	R	B
Walpepup	31/05/1999	Amethyst	40	190	Full	R	B
Walpepup	31/05/1999	Barwon	40	190	Full	R	B
Walpepup	12/05/2000	Amethyst	27	190	Full	R	B
Walpepup	12/05/2000	Barwon	27	190	Full	R	B
Tamworth	14/06/2000	Amethyst	39	190	2/3rd	R	B
Tamworth	14/06/2000	Barwon	39	190	2/3rd	R	B
Warwick	31/05/1999	Amethyst	45	190	Full	R	B
Warwick	31/05/1999	Barwon	45	190	Full	R	B
Warwick	5/06/2000	Amethyst	37	190	Full	R	B
Warwick	5/06/2000	Barwon	37	190	Full	R	B
Redland	2/04/1990	Amethyst	35	140	Full	I	C
Redland	10/07/1990	Amethyst	35	140	Full	I	C
Redland	24/07/1991	Warwick	35	240	Full	I	C

PAWC, Plant-available water-holding capacity. Water status: R, rainfed; I, Irrigated; *irrigated to full profile at planting; A, C. Douglas, QDPI&F, pers. comm.; B, Berger *et al.* (2004); C, Thomas and Fukai (1995).

pre-sowing rainfall to be accounted for. Sowing date, plant population and the amount of applied irrigation were specified in the manager module. Weather data were downloaded from the 'SILO' weather site (SILO 2005). Where available, rainfall and temperature data collected from the trial sites' were patched onto the weather data obtained from 'SILO'. Separate runs were made using both original and modified cultivar parameters.

For the Indian locations, maturity data from the chickpea trials by the All India Coordinated Program conducted at Coimbatore, Hisar, Jabalpur, Ludhiana, Patancheru and Rahuri during 1986–2002 were averaged. These were regressed against the mean time to maturity simulated by the APSIM chickpea model.

Homoclime analysis

Homoclime analysis was conducted on 67 locations in Australia, including those used for validating the model, and 24 locations in India (Table 2). The Indian locations represented a range of chickpea growing regions; however there were only a limited number of sites, especially in central and northern India that could be included, due to a paucity of quality climatic data. Climatic data of a larger number of locations were available from Australia to adequately cover the diversity of chickpea growing environments. Daily climatic databases of Australian locations were obtained from the Queensland Department of Natural Resources (SILO 2005), and for India from the National Ocean and Atmospheric Administration in the USA, and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India. Weather data of all the Australian locations covered the period from 1957 to 2005, however for the Indian locations time spans varied from 8 to 100 years.

The APSIM chickpea model was run for three soils of 100, 150 and 190 mm plant available water holding capacities (PAWC). Since chickpea grain yield is known to vary linearly in response to water supply (Johansen *et al*. 1994; Zhang *et al*. 2000) these three soils were expected to cover a range of crop responses to variation in PAWC. For each location, a plant density of 35 plants/m^2 was used. The two cultivars chosen for this analysis represented the extremes of slow and quick maturity types that have so far been parameterized. In order to reduce the complexity that could arise due to different crop rotations practiced in India, the winter chickpea-summer fallow system, which is the most common chickpea cropping system across the two countries, was simulated. Sowings were simulated

Table 2. Australian and Indian locations and their latitudes (degree decimals) and longitudes (degree decimals) in different states included in the homoclime analysis

Australian locations						Indian locations		
Location	Lat. (S)	Long.	Location	Lat. (S)	Long.	Location	Lat. (N)	Long.
Queensland[A]			**Victoria**			**Punjab**		
Banana	24.5	150.1	Bendigo	36.8	144.3	Ludhiana	30.9	75.9
Bendee	23.8	148.4	Beulah	35.9	142.4	Amritsar	31.6	74.9
Billa billa	28.2	150.4	Kalkee	36.3	142.1	**Haryana**		
Biloela	24.4	150.5	Mildura	34.2	142.1	Hisar	29.2	75.7
Bundaberg	24.9	152.4	Shepparton	36.4	145.4			
Capella	23.1	148	Swan Hill	35.3	143.6	**Delhi**	28.7	77.2
Cecil Plains	27.5	151.2	Walpeup	35.1	142	**Madhya Pradesh**		
Clermont	22.8	147.6	**South Australia**			Indore	22.7	75.8
Condamine	27.7	151.3	Eyre Peninsula	33.6	135.9	Jabalpur	23.2	80
Dalby	27.2	151.3	Gawler	34.6	138.7	**Andhra Pradesh**		
Dysart	22.6	148.4	Gladstone	33.3	138.4	Nandyal	15.3	78.4
Emerald	23.5	148.2	Hart	33.5	138.3	Patancheru	17.3	78.2
Gindie	23.7	148.1	Horsham	36.7	142.1	**Maharashtra**		
Gogango	23.7	150.1	Minnipa	32.8	135.2	Parbhani	15.1	75.1
Goondiwindi	28.5	150.3	Nonning	32.5	136.5	Solapur	17.7	75.9
Jimbour	27	151.2	Port Lincoln	34.7	135.9	Mohol	17.8	75.5
Moonie	27.6	150.4	Rosedale	34.6	138.8	Jeur	18.2	75.2
Moura	24.6	150	**Western Australia**			Rahuri	19.4	74.7
Orion	24.3	148.4	Bindi Bindi	30.6	116.4	Aurangabad	20	75.3
Roma	26.6	148.8	Cunderdin	31.7	117.3	**Karnataka**		
St George	28	148.6	Esperance	33.6	121.8	Banglore	13	77.6
Surat	27.2	149.1	Geraldton	28.8	114.7	Annigeri	15.1	75.1
Thallon	28.6	148.9	Gnowangerup	33.9	118	Bellary	15.2	76.9
Theodore	25	150.1	Kununurra	15.8	128.7	Hagari	15.2	77.1
Warwick	28.2	152.1	Lake Grace	33.1	118.5	Dharwad	15.4	75.1
New South Wales			Merredin	31.5	118.2	Raichur	16.2	77.4
Coleambally	34.8	145.9	Mullewa	28.5	115.5	Bheemar	16.6	76.8
Coonamble	31	148.4	Northam	31.6	116.7	Bijapur	16.8	75.7
Griffith	34.3	146.1	Nyabing	33.5	118.2	Gulbarga	17.4	76.9
Hay	34.5	144.9	Pingaring	32.8	118.6	**Tamil Nadu**		
Moree	29.5	149.8	Three Springs	29.5	115.8	Coimbatore	11.7	77.1
Narrabri	30.3	149.8	Varley	32.8	119.5			
Narromine	32.2	148.2	West Miling	30.4	116.3			
Tamworth	31.1	150.9	Wyndham	15.5	128.1			
W. Wagga	35.2	147.5						
Walgett	30	148.1						

[A] State names are in bold letters.

to take place whenever the soil had accumulated 90 mm of extractable soil water (ESW) between 15-May and 14-June in Australia, and 15-Oct and 14-Nov in India. If this condition was not met until the last day of the respective sowing window in each country, then sowing was initiated with 30 mm irrigation on the following day, disregarding the ESW constraint. Pre-sowing irrigation is not uncommon in India where gaps in the timing of the monsoon withdrawal and chickpea sowing can be large leaving inadequate seedbed soil moisture. However, in Australia pre-sowing irrigation is generally rare; but it was included to capture the climatic effect of all seasons, as for India, in the event of insufficient seedbed moisture which would be equivalent to about a week's moisture supply.

A range of outputs was simulated. However, only time to flowering, maturity and grain yield, which are normally recorded in any breeding trial and were expected to capture the integrated effect of plant, soil and weather interactions, were used for homoclime analysis. The means of the annual outputs of these characters comprising 18 variables (3 soil types × 2 cultivars × 3 observations), were clustered using hierarchical complete linkage clustering (Wards method). The number of meaningful clusters was determined on the basis of scree-plot pattern (Cattell 1966).

To determine climatic and biological characteristics of different homoclimes, the averages of pre-season rain, pre-anthesis rain, post-anthesis rain, lowest minimum temperature, minimum temperature at germination, minimum and maximum temperatures at 1st pod set, moisture availability index (water supply/water demand) for the last 60 days, times to first flowering, first pod set and maturity, grain yield and biomass were compared among different clusters. The differences among clusters were analysed using Genstat's (version 9.2, Lawes Agricultural Trust, Rothamsted Experimental Station, UK) unbalanced analysis of variance procedure with clusters as factors and values for different soil types as replications. This computed maximum, minimum and average least significant difference at 5% probability level, but only average values were retained for comparison.

Results and discussion

Model validation for the target environments

The APSIM chickpea model was reported to predict flowering time and grain yield reasonably well, but was not able to predict maturity accurately when ambient temperature was <15°C during the reproductive phase (www.apsim.info/apsim/publish/apsim/chickpea). Indeed in the present study, the ability of the model to predict time to maturity with the original cultivar parameters was poor ($R^2 = 0.49$), as it was unable to simulate delayed maturity in longer season environments (Fig. 2). A conspicuous outlier was that of Redland Bay, which was a long season site with mean ambient temperatures frequently falling to <15°C during the reproductive phase. The unmodified APSIM model did not simulate maturity very well at this site because it did not account for the delay in pod set caused by the crop's exposure to chilling temperatures. The chilling sensitivity of chickpea was better captured by the modified model without affecting yield simulation. This was evident by improvement in the prediction of maturity ($R^2 = 0.65$) because it increased thermal time targets of the post-flower-initiation phases when mean ambient temperature was <15°C (Fig. 2). With the modified model, simulated maturity tended to be slightly more than the observed maturity in some locations, which to some extent could be related to subjectivity introduced in assessing maturity based on the external pod or crop colour by different individuals across sites.

Using the modified cultivar parameters, the model was still able to predict grain yield with a similar level of accuracy as achieved by the original parameters; hence these parameters were retained for subsequent homoclime analysis. The model, with the modified cultivar parameters accounted for 92% of the total variation in time to maturity for six Indian locations (Ludhiana, Hisar, Jabalpur, Rahuri, Patancheru, and Coimbatore) for which mean maturity data were available from various variety evaluation trials (data not shown).

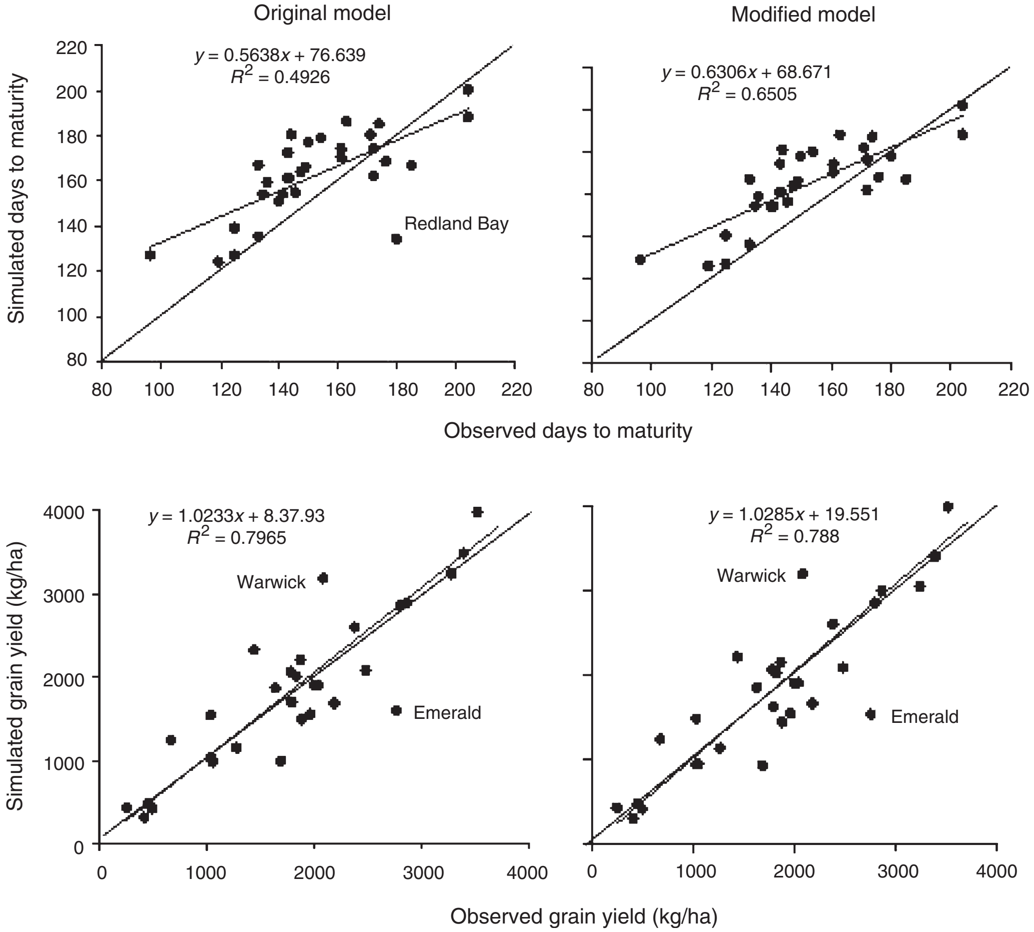
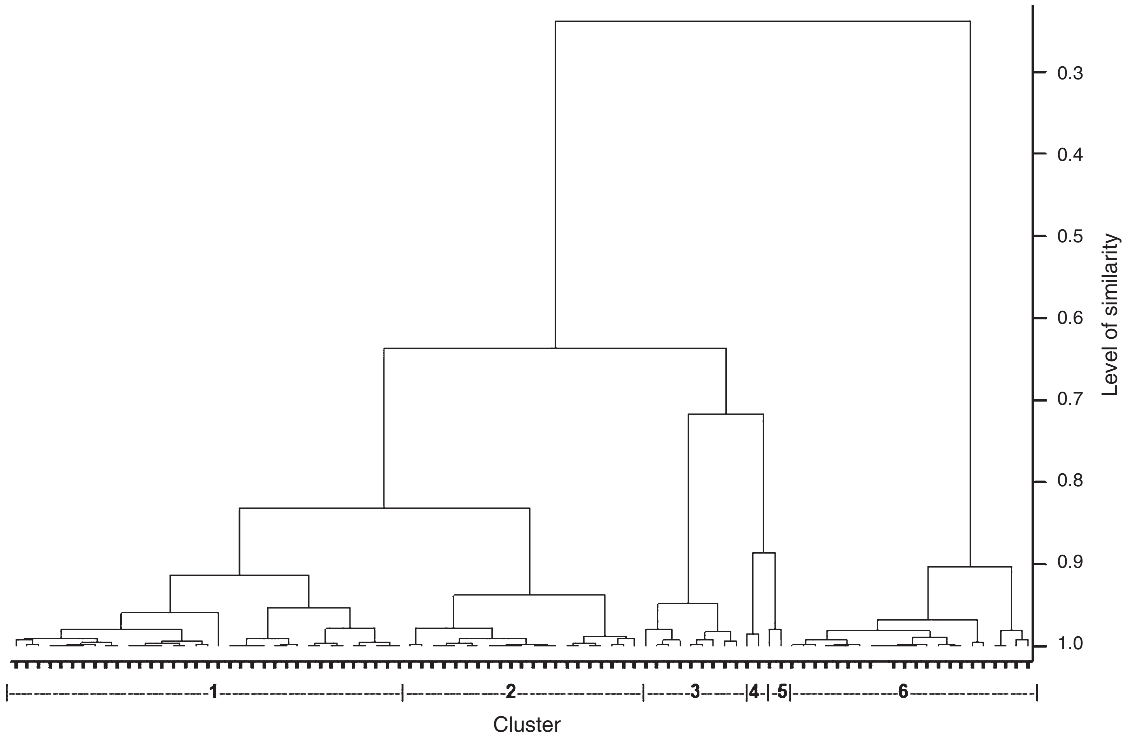


Fig. 2. Observed and simulated time to maturity and grain yield of chickpea in sowings across Australia (see Table 1 for details) during 1999–2005 using original (left) and modified (right) cultivar parameters. A few outliers in maturity and yield are also shown.

Homoclime analysis

The cluster analysis of means of the APSIM simulated flowering and maturity and grain yield separated 91 locations of the two countries into 6 clusters at a 90% level of similarity (Fig. 3). The membership of clusters 1, 2, and 6 was relatively large and that of clusters 4 and 5 the smallest. The Australian locations were present in all the six clusters whereas the Indian locations were only present in clusters 1, 2 and 6. This suggests that Australian chickpea growing environments are relatively more diverse than Indian environments. The inclusion of locations of both countries in three clusters suggests that some of the Australian locations should have similar growing environments as experienced by chickpea in some locations in India. Such locations can be considered as homoclimes because their environments produced similar outcomes of flowering, maturity, as well as grain yield using the APSIM model. Malhotra and Singh (1991) have used flowering and grain yield from two international yield trials to characterise chickpea growing environments. However, in many environments, flowering commences whenever its thermal time target is reached. However, in reality pod setting is delayed due to cooler temperatures which may affect maturity. To account for this variation in the period between commencement of flowering and pod-set, the inclusion of maturity was considered appropriate in the present study.

The memberships of individual clusters followed a systematic geographic pattern in both countries (Fig. 4). In India, clusters 1 and 2 covered 4 subtropical northern Indian locations, and cluster 6 all the rest of the locations in the tropics (Fig. 4). In Australia, distribution of locations also appeared to be influenced by different agro-ecological conditions. For example in cluster 1, locations were found mainly in the semi-arid tropical, subtropical and temperate slopes and plains; cluster 2 locations were mainly in the subtropical and tropical slopes and plains; cluster 3 mainly in the temperate highlands on the eastern coast; cluster 4 on the wet-subtropical eastern and western coast; cluster 5 on wet southern temperate coast; and, cluster 6 in the north-west wet/dry tropics (Fig. 4). The spread of clusters 2 and 3



Cluster 1

Ludhiana
Amritsar
Kalkee
Beulah
Swanhill
Walpeup
Coleambally
Hay
Griffith
Mildura
Gnowangerup
Eyre Peninsula
Nyabing
Hart
Gladstone
Lake Grace
Variey
Pingaring
Nonning
Norham
Merredin
Coonamble
Narrabri
Walgett
Moree
Thallon
Goondiwindi
Billa billa
Condamine
Moonie
Cecil Plains
Dalby
Surat
Jimbour
Roma

Cluster 2

Delhi
Hisar
Minnipa
Cunderdin
Bindi Bindi
West Milling
Three Springs
Mullewa
St George
Theodore
Moura
Banana
Biloela
Orion
Bendee
Gindie
Gogango
Emerald
Capella
Clermont
Dysart

Cluster 3

Bendigo
Horsham
Shepparton
W. Wagga
Gawler
Rosedale
Narromine
Tamworth
Warwick

Cluster 4

Geraldton
Bundaberg

Cluster 5

Port Lincoln
Esperance

Cluster 6

Banglore
Annigeri
Parbhani
Bellary
Hagari
Nandyal
Dharwad
Raichur
Bheemar.
Bijapur
Coimbatore
Patancheru
Gulbarga
Solapur
Mohol
Jeur
Rahuri
Aurangabad
Indore
Jabalpur
Kununurra
Wyndham

Fig. 3. Hierarchical cluster analysis of 67 locations in Australia and 24 locations in India based on Ward's method, for flowering, maturity and grain yield. The Indian locations are in italics. The clustering was done at 90% level of similarity.

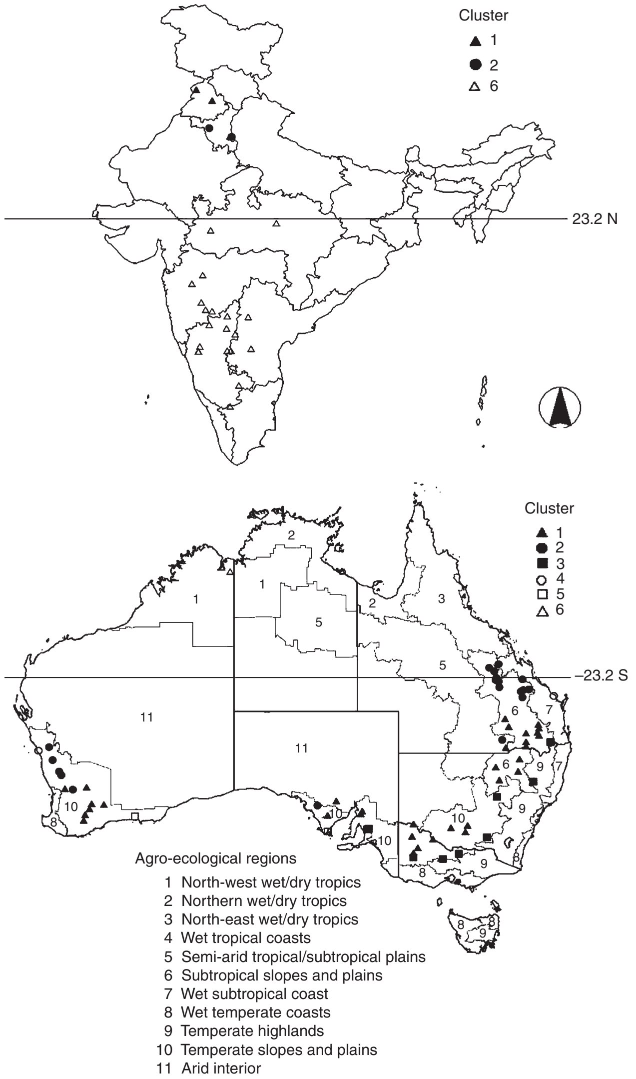


Fig. 4. Geographic spread of different clusters across India and Australia. See Fig. 3 for the names of locations within each cluster. Locations within and across the two countries with a similar cluster symbol are homoclime.

covered the widest range of subtropical (northern), temperate and the Mediterranean type environments in Australia where much of the current chickpea production occurs.

The clusters differed in biological and physical characteristics (Table 3). Biomass was at its maximum in cluster 5 and lowest in cluster 6 locations. The crop flowered and matured the earliest in cluster 6 and the latest in cluster 3, with this difference being about 2-fold. The period of ineffective flowering of 34 days (difference in anthesis and pod-set) was the longest in cluster 3 locations which spread in the cool sub-tropical and temperate highlands on the eastern coast of Australia. Grain yields were the lowest for cluster 6 and were ~27% of cluster 5, which had the highest grain yield. The mean of cluster 1 grain yield was ~40% higher than the grain yield mean of cluster 2. Regan *et al.* (2006) reported that grain yield of crops grown on northern latitude locations in south-Western Australia that belonged to cluster 2 in our study (see Fig. 4) were generally higher than those on cooler southern latitudes that belonged to cluster 1, especially in autumn sowings. This was not supported by the model simulations in our study although duration of the crop simulated was indeed longer in cluster 1 locations. As noted earlier, the model does not account for local specific constraints related to pests and diseases or lodging and hence there could be some discrepancy in the observed and simulated performance of the crop for these reasons.

On the basis of climatic analysis Berger and Turner (2007) grouped the world's chickpea growing region into four common rainfall and temperature categories namely, Mediterranean type – cool or warm climate; and summer dominant rainfall – cool or warm climate. According to their analysis Indian environments largely fall in to the summer dominant rainfall-cool and warm environments and Australian environments into both summer-dominant and the Mediterranean type – cool and warm environments. Regan *et al.* (2006) recently reported that within the narrow range of the Mediterranean type environments of south-western Australia, chickpea growing regions could be divided into warm northern, intermediate central and cooler southern region. Our analysis confirms the separation of the northern locations from the southern region by placing them in different clusters. The northern locations within the Mediterranean type environments were in the same cluster as the central Queensland locations. The analysis grouped two locations such as Merredin and Northam in cluster 1, but a nearby location at Cunderdin in cluster 2. Regan *et al.* (2006) had placed all the three locations in a separate 'central' group which in their study behaved somewhat similar to northern locations in early sowings, and to southern locations for the late sowings. As different sowings were not simulated in our study, this was not assessed.

The locations in subtropical Queensland and New South Wales with a summer dominant rainfall pattern were in cluster 1, 2 and 3. Also, the locations with warmer central Queensland were in cluster 2 and those of cooler south-eastern Queensland in clusters 1 and 3. A somewhat surprising result of this analysis, as noted above, was that several locations in central Queensland homoclimed (present in the same cluster 2) with locations in the Mediterranean type environments of south-western Australia and Minnipa in South Australia and in northern India (Figs 3 and 4). It is in this region of Queensland that the chickpea area is currently expanding. This suggests that a cultivar adapted to one of these homoclimes could find adaptation in the central Queensland regions. Supportive evidence for this hypothesis came from a recent release of the variety 'Moti' in central Queensland, which was originally bred and selected in south-western Australia (Berger *et al.* 2004). For locations of this cluster, terminal drought may be a major issue as suggested by the low moisture availability index during the reproductive period and hence development of early maturing cultivars that can escape terminal drought may be advantageous.

Two Australian locations in cluster 3, Warwick and Tamworth, where much of the chickpea breeding work is currently concentrated, did not cluster with any of the locations from Western Australia, or any other locations in

Table 3. Means of biological and physical characteristics in different clusters

Characteristics	Clusters						
	#1	#2	#3	#4	#5	#6	l.s.d.
Biological							
Anthesis	100	80	112	77	95	54	0.9
Biomass (t/ha)	4	3.82	5.01	5.86	6.66	2.83	0.101
Grain yield (t/ha)	1.25	0.89	1.9	1.86	2.66	0.74	0.051
Days to first pod-set	130	108	144	105	127	78	0.9
Days to maturity	170	146	187	145	172	112	0.9
Physical							
Germination Min T. (°C)	7.2	11.2	6.2	13.2	8.9	19.5	0.22
Min. Crop Temp. (°C)	–1.7	0.2	–1.8	4	3.2	9.5	0.15
Max. T at podding (°C)	25.2	26.4	23.4	23.2	21.2	29.6	0.29
Min. T at podding (°C)	10.2	10.7	9.6	11.2	10.2	14.9	0.28
Average Max. T (°C)	21.1	24.6	18.7	22.5	18.7	30	0.11
Average Min. T (°C)	7.4	9.4	6.8	11.2	9	16.1	0.11
Pre-season rain (mm)	119	146	127	219	133	338	9.6
Post-anthesis rain (mm)	83	54	112	73	97	17	3.5
Pre-anthesis rain (mm)	121	69	188	179	209	75	5
Moisture availability index	0.54	0.43	0.68	0.59	0.72	0.56	0.014

l.s.d. = average least significant difference at 5% probability.

south-eastern or central Queensland. Based on the analysis of genotype × environment interaction for grain yield in chickpea trials conducted in Australia, Berger *et al.* (2004) suggested that Tamworth may not be a representative site for developing cultivars that are better adapted to other environments in Western Australia and Queensland. Our homoclime grouping therefore supports their suggestion and further indicates that Warwick may also not be a representative site for selecting material adaptation in many other Queensland locations in cluster 1 and 2, as it does not homoclime with them.

Implications for chickpea improvement

The earlier work on chickpea has recognised that the grouping of homogenous environments can minimize genotype × environment interactions in chickpea (Malhotra and Singh 1991). Hence a genotype developed at one location can be expected to perform well at other locations within the homoclime group. However, the usefulness of this type of homoclime analysis based on simulated outputs to breeders/agronomists will be more easily apparent if it can be shown that germplasm adapted to one homoclime location will indeed do well in other homoclime locations. A few examples of past releases tend to support this indirectly. For example, ‘Tyson’ which originated from Ludhiana in N. India (Beech and Brinsmead 1980) which fell in cluster 1 environment, was released in cluster 1 – south-east Queensland locations in 1978. Within India, several lines developed in central India, e.g. JG 62 and ICC 4958 have been found to be better adapted to southern India (Saxena 2003; Berger *et al.* 2006). Berger *et al.* (2006) reported that several chickpea cultivars that did well in locations in both central and southern India were in the same cluster, suggesting similar adaptation strategies, e.g. high harvest index and early flowering employed by cultivars adapted to these regions.

Some chickpea cultivars could be suitable in more than one homoclime, if they have been bred in two different homoclime environments. For example, two recent G × E studies conducted in Australia and India (Berger *et al.* 2004, 2006) suggested that the chickpea line ICCV 10, which was bred through a shuttle breeding and selection program carried out at cluster 2 (Hisar) and cluster 6 (Patancheru) locations in India by ICRISAT, was found to have wider adaptation in locations of clusters 1 and 2 in Australia, as well as in cluster 6 in India. A similar strategy, in addition to involving more diverse parents, was adopted by the the Indian Agricultural Research Institute (IARI) New Delhi breeding program, with breeding and selection being completed in Delhi in the north, and Dharwad in south India (Berger *et al.* 2006). Cultivar BG 362 developed by this program was found to be high yielding in Australian environments included in clusters 1 and 2 (Berger *et al.* 2004). Several cultivars developed with a similar approach to this program have also been found to be widely adapted in India (Berger *et al.* 2006). Although it is yet to be confirmed, wider adaptation from the shuttle breeding approach seems arise from greater photoperiod sensitivity being incorporated through selection at higher latitudes/cooler environments. This probably enables these cultivars to achieve greater source and sink potential, and early flowering, as well as other drought avoidance characteristics through selection at lower latitudes in cluster 6 environments. In contrast, the germplasm originating only from the breeding programs within a homoclime e.g. cluster 6 locations of central and peninsular India, tends to be more specifically adapted to this region, as it seems to encourage development of traits that are relevant to adaptation in that environment (Berger *et al.* 2006). Such germplasm tends to perform poorly in cooler environments, which is probably associated with a lack of required photoperiod sensitivity.

In Australia, the national breeding program for chickpea is located at Tamworth, with a node in Queensland located at

Warwick, which both incidentally occur in cluster 3. Since these locations do not homoclime with locations in major chickpea growing areas in central Queensland, south-eastern Queensland, and Western Australia, materials bred at these locations may not find adequate adaptation in warmer or short growing environments of central and southern Queensland, as well as in WA. A shuttle breeding approach similar to that was adopted by ICRISAT, which was responsible for the breeding of ICCV 10, and that of BG lines developed by IARI, is likely to lead to development of cultivars that are more widely adapted to other homoclimes.

Conclusions

The APSIM chickpea model, with revised crop parameters, has been able to improve prediction of time to maturity without adversely affecting prediction of grain yield. This provided us greater confidence in conducting the homoclime analysis of different chickpea growing environments of India and Australia. Identification of homoclimes reported in this study seems to have arisen due to a better integration of interactions between diurnal and seasonal changes in climate, plant and soil attributes achieved through the use of the APSIM chickpea model. This would have been difficult to visualise by simply comparing climatic averages between locations. It is recognised that all locations, especially in India where chickpea is currently being grown, could not be included in this analysis due to a paucity of climatic data. Those locations could be part of the cluster in close proximity to them. Availability of daily climatic data would constrain wider applicability of this approach, but the potential benefits demonstrated in this study should encourage creation of such databases for most environments.

The homoclime analysis used in this study, and supported by some examples from previously published studies, suggests this approach may be useful for improving the efficiency of national and international germplasm exchanges, introduction of newly evolved high yielding cultivars in new environments and rationalizing breeding and testing sites. The analysis has generally been able to confirm observations made from the recent extensive field experimentation that analysed G × E interactions in chickpea (Berger *et al*. 2004, 2006). Further in-depth analysis of published or unpublished datasets, or new experiments, would be useful to further validate the conclusions of this study and confirm the value of the methodology used.

Use of only two genotypes in the study may be viewed as a limitation of this study. However, since the main objective of the study was to identify environmental similarity rather than evaluate cultivar performance across several environments, use of a wider range of cultivars was considered unnecessary. In the future, when more promising genotypes are parameterized for the APSIM chickpea model, it should become possible to evaluate their performance across different homoclimes using this approach.

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