

## RELATIVE PRODUCTIVITY, PROFITABILITY AND WATER USE EFFICIENCY OF CROPPING SYSTEMS IN HOT ARID INDIA

By V. S. RATHORE†, N. S. NATHAWAT, B. MEEL, B. M. YADAV  
and J. P. SINGH

*Regional Research Station, Central Arid Zone Research Institute, Bikaner,  
Rajasthan 334004, India*

*(Accepted 6 February 2014; First published online 27 March 2014)*

### SUMMARY

The choice of an appropriate cropping system is critical to maintaining or enhancing agricultural sustainability. Yield, profitability and water use efficiency are important factors for determining suitability of cropping systems in hot arid region. In a two-year field experiment (2009/10–2010/11) on loam sandy soils of Bikaner, India, the production potential, profitability and water use efficiency (WUE) of five cropping systems (groundnut–wheat, groundnut–isabgol, groundnut–chickpea, cluster bean–wheat and mung bean–wheat) each at six nutrient application rate (NAR) i.e. 0, 25, 50, 75, 100% recommended dose of N and P (NP) and 100% NP + S were evaluated. The cropping systems varied significantly in terms of productivity, profitability and WUEs. Averaged across nutrient application regimes, groundnut–wheat rotation gave 300–1620 kg ha<sup>-1</sup> and 957–3365 kg ha<sup>-1</sup> higher grain and biomass yields, respectively, than other cropping systems. The mean annual net returns were highest for the mung bean–wheat system, which returned 32–57% higher net return than other cropping systems. The mung bean–wheat and cluster bean–wheat systems had higher WUE in terms of yields than other cropping systems. The mung bean–wheat system recorded 35–63% higher WUE in monetary terms compared with other systems. Nutrients application improved yields, profit and WUEs of cropping systems. Averaged across years and cropping systems, the application of 100% NP improved grain yields, returns and WUE by 1.7, 3.9 and 1.6 times than no application of nutrients. The results suggest that the profitability and WUEs of crop production in this hot arid environment can be improved, compared with groundnut–wheat cropping, by substituting groundnut by mung bean and nutrients application.

### INTRODUCTION

Irrigation covers 20% of all cultivated land and accounts for about 40% of agricultural production (Molden, 2007). Irrigation accounts for ~70% of all the world's freshwater withdrawals. Rapidly increasing non-agricultural demands for water, changing food preferences and global climate changes have placed increasing pressure on scarce water resources (Rosegrant *et al.*, 2009). In order to sustain the rapidly growing world population, agricultural production need to increase (Howell, 2001), although the portion of freshwater currently available for agriculture is decreasing (Cai and Rosegrant, 2003). The problem of ensuring an adequate supply of agricultural

†Corresponding author. Email: rathoreiari@yahoo.co.in

products and protecting water resources is particularly acute in arid regions where water is the most limiting factor for crop cultivation.

The Indian hot arid region covers 31.7 million ha. About 62% of the total hot arid region is located in the state of Rajasthan, India. The arid Rajasthan is divided into the following four agro-climatic zones: (i) arid western plain, (ii) irrigated north-western plain, (iii) transitional plain of inland drainage and (iv) transitional plain of luni basin (Kathju *et al.*, 1998). Of those, arid western plain is the largest (12.37 million ha). It is primarily a rainfed crops (pearl millet, cluster bean, moth bean, sesame) growing area. Rainfed crop production is low, unstable and risky in this region (Rathore *et al.*, 2009). With the creation of irrigation facilities, the traditional rainfed crops, such as *Pennisetum typhoides*, *Vigna aconitifolia*, *Cyamopsis tetragonoloba* and *Sesamum indicum*, have been replaced with *Arachis hypogaea*, *Gossypium hirsutum*, *Triticum aestivum* and *Brassica juncea* (Joshi and Saxena, 1997). Irrigation water is a critical scarce resource in the state of Rajasthan, particularly in western arid and semi-arid regions (Singh *et al.*, 2010). Groundwater, which constitutes 52.3% share in the total irrigated area in north-western Rajasthan, is depleting at an alarming rate (Rathore, 2003). Groundnut (GN)–wheat (W) is a common cropping system in groundwater-irrigated area (Rathore *et al.*, 2010). Both these crops have high water requirement. The continuous cultivation of groundnut–wheat cropping system poses a serious threat to the sustainability of groundwater resource. Identification of suitable cropping systems that make the best use of water resources and provide higher yields and returns is important if the diverse needs of farming communities and environmental sustainability in arid regions are to be catered (Joshi *et al.*, 2009). Management inputs interact with cropping systems and dictate their efficiencies (Riedell *et al.*, 1998). Inherent poor soil fertility, particularly soils low in nitrogen, phosphorus and sulfur content, are another major factor responsible for low productivity of crops in hot arid regions. Therefore, simultaneous optimization of nutrient application and cropping systems will provide optimum yield and water use efficiency (WUE).

Most of the previous works on cropping systems in this region have focused on component crops of cropping systems; and further focused on a narrow range of criteria, e.g. yields, returns and the effect on soil properties of different cropping systems (Rao *et al.*, 1995; Saxena *et al.*, 1997; Singh *et al.*, 2008a). To date, very little information is available regarding the productivity, profitability and WUE of contrasting irrigated cropping systems in the hot arid region of India. This assessment is needed for understanding option for diversification in the region.

The present experiment was conducted with the objective of assessing yields, returns, and WUE of five cropping systems. This paper reports the results of field experiment that tested the hypothesis that a diversified rotation could provide yields (Y), WUE and net returns (NR) that matched or exceeded those from groundnut–wheat. Crop yields are reduced by nutrient deficiencies in Indian hot arid region (Faroda *et al.*, 2007), so this study also tested the hypothesis that nutrient management could also improve crop yields, profit and WUE. The results from this study facilitate the selection of efficient cropping systems and nutrient management options in iso-agroclimatic regions of the world.

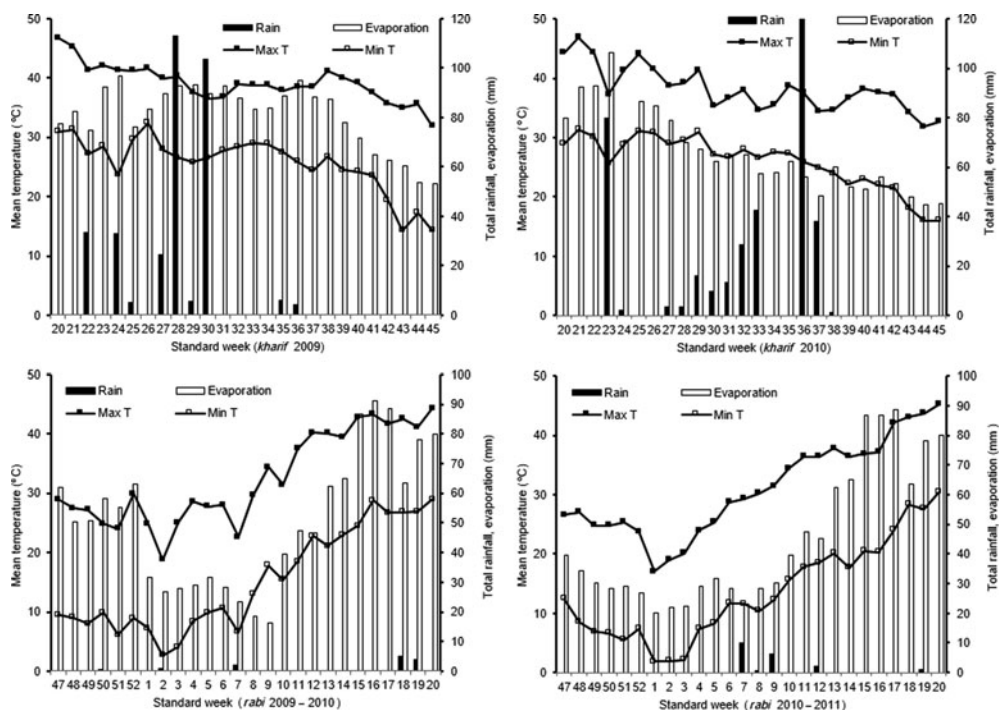


Figure 1. Weekly rainfall, evaporation and temperatures over the two-year study period at Bikaner, India.

## MATERIALS AND METHODS

### Study environment

This study was conducted over a two-year period (2009–2010 to 2010–2011) at CAZRI, Regional Research Station, Bikaner, India, FPARP's site Geegasar (27°9'N; 73°4'E; alt. 238.3 metres above sea level (masl)) in north-western Rajasthan, India. The climate of experimental site is hot arid with an average annual precipitation of 287 mm and an average air temperature of 25.1 °C. More than 85% of the total annual rainfall is received during the south-west monsoon season (July to September). The weather data for the crop growing seasons during the two-year experiment are presented in Figure 1. The soil was Torripssamentes typic with the following key properties for the 0- to 20-cm layer: pH (soil/H<sub>2</sub>O, 1:2.5): 8.4, organic carbon: 1.1 g kg<sup>-1</sup> (the Walkley–Black method), available Phosphorus: 4.7 mg kg<sup>-1</sup> (Olsen) and available potassium: 100.5 mg kg<sup>-1</sup> (1 N NH<sub>4</sub> acetate), available sulfur: 3.3 mg kg<sup>-1</sup>; texture was loamy sand, with sand (2000–50 μm), silt (50–2 μm) and clay (<2 μm) content: 854, 51 and 95 g kg<sup>-1</sup> respectively.

### Treatments and experimental design

There were two factors in the experiment. The first factor was cropping systems (CS). The five cropping systems tested used six crops: GN (*Arachis hypogaea* L.), mung bean (*Vigna radiata* (L.) Wilczec) (hereafter MB), cluster bean (*Cyamopsis tetragonoloba*

(L.) Taub.) (hereafter CB), wheat (*Triticum aestivum* L.), isabgol (*Plantago ovata* Forsk.) (hereafter IG) and chickpea (*Cicer arietinum* L.) (hereafter CP). The rotations followed were: GN–W, GN–IG, GN–CP, CB–W and MB–W. The second factor was nutrient application rate (NAR) with six treatments: 0, 25, 50, 75, 100% of recommended N and P (NP) dose and 100% of NP + S for each crop grown in rotation (hereafter 0, 25, 50, 75, 100% NP and 100% NP + S respectively). The experimental design was a split-plot with three replications. Cropping systems was assigned to main plot and nutrient application rates to sub plot.

Size of main plot was 100.0 × 9.0 m whereas that of sub-plot was 15.0 × 9.0 m with 2-m gap in-between. Each sub-plot was bordered with an earth dike of 30 cm in height. Overall, six sub-plots were randomly laid out in each main plot, which resulted into a total of 90 sub-plots for the whole experiment. Main plots and sub-plots were randomly assigned during the first year of the study. Thereafter, individual sub-plot with particular CS × NAR combinations was assigned with the same experimental unit during successive year.

#### *Crop management practices and yield measurements*

Crop cultivars, planting time, seeding rates, spacing and fertilizer application rates are shown in Table 1. The land was prepared by a tractor-drawn disc harrow. Urea and di-ammonium phosphate fertilizers were used to supply nitrogen and phosphorus respectively. Irrigation was applied via sprinkler method. The water was applied at the rate of 500 m<sup>3</sup> ha<sup>-1</sup> per irrigation. Application of water is measured with water meter. Crop yields of grain (in case of groundnut pod) and straw were determined at the physiological maturity stage from each sub-plot. Grains/pods were separated manually after harvesting. Sub-samples of main yield (grain/pod) and by-products (straw) were oven-dried to a constant weight at 70 °C and expressed as kg ha<sup>-1</sup> (Table 2).

#### *Determination of productivity and profitability*

Total biomass yields (BY) were measured by totalling the grain/(pod in case of groundnut) and straw yields (SY) of the individual crops. Yields (grain yield (GY) and biomass yield (BY)) of each cropping system were measured by totalling yields of *kharif* and *rabi* seasons crops of rotation in the year:

$$GY = GY_1 \text{ ha}^{-1} + GY_2 \text{ ha}^{-1}, \quad (1)$$

$$BY = BY_1 \text{ ha}^{-1} + BY_2 \text{ ha}^{-1}, \quad (2)$$

where GY and BY are in kg ha<sup>-1</sup> and subscripts '1' and '2' represent the *kharif* and *rabi* seasons crops respectively.

Costs of cultivation (CC) and returns of crops were calculated on the basis of prevailing market prices for inputs and outputs. Net returns were calculated by subtracting production costs from the gross value of the produce (main and

Table 1. Management practice for individual crops grown in field experiment.

Crop	Cultivar	Seed rate (kg ha <sup>-1</sup> )	Spacing (cm)	Crop season (seed to seed) <sup>†</sup>	Nutrient application rate (N–P–S, kg ha <sup>-1</sup> )*	Time of fertilizer application	Number of weeding/intercultural operations
Groundnut	GG-20	80	45 × 15	May (3)–October (4)	40–17.9–20	Nitrogen + Phosphorus + S as basal	4
Cluster bean	HG-365	18	30 × 10	July (2)–October (4)	20–17.2–10	Nitrogen + Phosphorus + S as basal	2
Mung bean	SML-668	18	30 × 10	July (3)–October (3)	20–17.2–10	Nitrogen + Phosphorus + S as basal	2
Wheat	Raj-1482	110	25 × 5	November (3)–April (2)	120–17.2–10	½ Nitrogen + Phosphorus + S as basal; ¼ Nitrogen at 25 DAS**; ¼ Nitrogen at 45 DAS	2
Chickpea	RSG-888	80	30 × 10	November (1)–March (2)	20–13.8–10	Nitrogen + Phosphorus + S at basal	2
Isabgol	GI-2	5	30 × 5	November (3)–April (1)	40–10.3–10	½ Nitrogen + Phosphorus + S as basal; ½ N and at 30 DAS	2

<sup>†</sup>Figure in parenthesis indicate week of the month.

\*Nitrogen and phosphorus were applied as urea and di-ammonium phosphate respectively. The fertilizers were applied as per treatment.

\*\*DAS: days after sowing.

Table 2. Duration and yields of crops in different cropping systems during two cropping years at Bikaner, India.

Cropping system	2009–2010						2010–2011					
	Kharif			Rabi			Kharif			Rabi		
	GN	CB	MB	W	IG	CP	GN	CB	MB	W	IG	CP
	Duration (days)											
	165	105	96	130	125	120	158	100	90	120	115	109
	Grain yield (kg ha <sup>-1</sup> y <sup>-1</sup> )											
GN <sup>†</sup> –W	1523 <sup>c*</sup>	–	–	2133 <sup>c</sup>	–	–	1311 <sup>c</sup>	–	–	1976 <sup>c</sup>	–	–
GN–IG	1531 <sup>c</sup>	–	–	–	484 <sup>a</sup>	–	–	–	–	–	363 <sup>a</sup>	–
GN–CP	1556 <sup>c</sup>	–	–	–	–	1364 <sup>b</sup>	–	–	–	–	–	1185 <sup>b</sup>
CB–W	–	1255 <sup>b</sup>	–	2103 <sup>c</sup>	–	–	–	991 <sup>b</sup>	–	1994 <sup>c</sup>	–	–
MB–W	–	–	1126 <sup>a</sup>	2158 <sup>c</sup>	–	–	–	–	858 <sup>a</sup>	1988 <sup>c</sup>	–	–
	Straw yield (kg ha <sup>-1</sup> y <sup>-1</sup> )											
GN–W	2976 <sup>c</sup>	–	–	3158 <sup>c</sup>	–	–	2111 <sup>c,d</sup>	–	–	2784 <sup>c</sup>	–	–
GN–IG	3015 <sup>c</sup>	–	–	–	1357 <sup>a</sup>	–	–	–	–	–	1079 <sup>c</sup>	–
GN–CP	3029 <sup>c</sup>	–	–	–	–	1919 <sup>b</sup>	–	–	–	–	–	1665 <sup>a</sup>
CB–W	–	1954 <sup>a</sup>	–	3186 <sup>c</sup>	–	–	–	1807 <sup>a</sup>	–	2769 <sup>b</sup>	–	–
MB–W	–	–	2094 <sup>b</sup>	3193 <sup>c</sup>	–	–	–	–	1973 <sup>b</sup>	2806 <sup>c</sup>	–	–

<sup>†</sup>In each cropping system the first crop is grown in kharif season and the second crop is grown in rabi season.

\*Values are mean yield averaged across nutrient application rate; in case of groundnut, the pod yield is mentioned instead of grain yield. Mean values within each cropping season in particular year followed by different superscript alphabets are significantly different at  $p \leq 0.05$  according to least significant difference (LSD).

by-products) for each of the crops:

$$NR = \{(GY)(Pg) + (SY)(Ps)\} - \{CC\}, \quad (3)$$

where SY is the straw yield ( $\text{kg ha}^{-1}$ ), Pg is the price of grain (in Rs.  $\text{kg}^{-1}$ ), Ps is the price of straw (in Rs.  $\text{kg}^{-1}$ ) and CC is also in Rs  $\text{ha}^{-1}$ . Net returns on the rotation basis were calculated as follows:

$$NR = NR_1 + NR_2, \quad (4)$$

where subscripts '1' and '2' represent the kharif and rabi seasons crops respectively.

Return on investment (RI) for each crop was calculated as follows:

$$RI = 100 \times (NR/CC), \quad (5)$$

where RI is expressed in percentage, NR in Rs.  $\text{ha}^{-1}$  and CC is expressed in Rs.  $\text{ha}^{-1}$ . We also evaluated economic performance of the cropping systems for a range of product prices (representing two standard deviations lower to two standard deviations higher than their respective mean values) to test the sensitivity of net returns to changes in selected price conditions according to the procedure followed by Zentner *et al.* (2006).

#### *Determination of water use efficiency*

Soil water content was measured gravimetrically down to 1.25-m depth. Soil samples were taken with a tube auger. Evapotranspiration (ET) values were used to compute the water use. ET was estimated using a standard water balance equation:

$$P + I + U = R + D \pm \Delta W + ET, \quad (6)$$

where, P = precipitation (mm), I = amount of irrigation (mm), U = upward flux (mm), R = surface runoff (mm), D = water lost by deep percolation (mm),  $\Delta W$  = change in soil water storage between planting and harvesting of the crop.

It was assumed that there was negligible upward flux beyond the measured depth. This is because the level of the water table near the experimental field was never closer than 3.0 m. Surface runoff (R) was assumed to be zero as the soil at the experimental site was loam sandy, had a good infiltration rate and each sub-plot was protected by a 35-cm bund. Deep percolation (D) was assumed to be negligible since the water storage capacity of soil at the experimental site was high. Therefore, U, R and D were taken as zero. Thus, Eq. (6) reduces to the following form for calculating ET:

$$ET = I + P \pm \Delta W. \quad (7)$$

The value of ET was considered to be equivalent to the volume of water used (WU) by the crops.

Water use efficiency was calculated for both individual crops and rotation system as a whole. For individual crop, WUE was determined by dividing yields (GY, BY) and

returns by ET as follows:

$$\text{WUE} = Y(\text{GY or BY}) \text{ or NR/ET} \quad (8)$$

where Y is the yield (GY or BY in kg ha<sup>-1</sup>) and ET is the water use (mm) of crop. The WUE on the rotation system basis was total yield (GY or BY) or total return for a rotation cycle of the system divided by the sum of the ET of each crop (Peterson *et al.*, 1996):

$$\text{WUE} = (Y_1 + Y_2) \text{ or NR}_1 + \text{NR}_2 / \text{ET}_1 + \text{ET}_2, \quad (9)$$

where subscripts '1' and '2' represent the kharif and rabi crops respectively.

### *Data analysis*

All the measured parameters under the various treatments were tested for significant differences using analysis of variance (ANOVA) for a split-plot in Randomized Complete Block Design (RCBD), where significant separation of treatment means was achieved by the procedure of Fisher's least significant difference (F-LSD);  $p = 0.05$  was used as a critical limit for distinguishing the degree of variance between means.

## RESULTS

### *Climatic condition*

Annual precipitation totalled 333.8 mm and 412.5 mm in the 2009–2010 and 2010–2011 cropping years, compared with historical average of 287 mm (1901–1998). However, the rainfall pattern showed monthly variability between the two growing years (Figure 1). In 2009–2010 about 95% of seasonal rain occurred between May and July. In 2010–2011, about 88% of rain occurred between June and September. In July, rain was above the long-term average in 2009–2010, but it was below the long-term average in 2010–2011.

### *Productivity*

The yields of crops were higher in 2009–2010 than 2010–2011. The GY of crops varied from 363 kg ha<sup>-1</sup> to 2158 kg ha<sup>-1</sup>. The SY varied from 1079 kg ha<sup>-1</sup> to 3193 kg ha<sup>-1</sup> (Table 2). Among kharif season crops, groundnut gave higher yields (both GY and SY) compared with cluster bean and mung bean during both years. In the rabi season, wheat had the highest yields followed by chickpea and isabgol (Table 2). Cropping systems, nutrient application rate and their interaction (CS × NAR) had significant effects ( $p \leq 0.05$ ) on yields during both years (Table 3). The GY was significantly different ( $p \leq 0.05$ ) between the cropping systems. Averaged across NAR treatments and years, mean annual GY were the highest for GN–W (3471 kg ha<sup>-1</sup>) followed by CB–W (91% of GN–W), MB–W (88% of GN–W), GN–CP (78% of GN–W) and GN–IG (53% of GN–W). The GY increased linearly with an increase in NAR. Averaged across the years and cropping systems, application of



Table 3. Main effects of cropping systems (CS) and nutrient application rates (NAR) on grain yield (GY), straw yield (SY) and biomass yield (BY) during two cropping years at Bikaner, India.

Treatment	2009–2010			2010–2011		
	GY (kg ha <sup>-1</sup> )	SY (kg ha <sup>-1</sup> )	BY (kg ha <sup>-1</sup> )	GY (kg ha <sup>-1</sup> )	SY (kg ha <sup>-1</sup> )	BY (kg ha <sup>-1</sup> )
	Cropping system (CS)					
GN–W*	3656 <sup>ef</sup>	6134 <sup>c</sup>	9790 <sup>d</sup>	3286 <sup>c</sup>	4894 <sup>c</sup>	8180 <sup>d</sup>
GN–IG	2014 <sup>a</sup>	4372 <sup>a</sup>	6386 <sup>a</sup>	1689 <sup>a</sup>	3166 <sup>a</sup>	4855 <sup>a</sup>
GN–CP	2921 <sup>b</sup>	4948 <sup>b</sup>	7869 <sup>b</sup>	2521 <sup>b</sup>	3802 <sup>b</sup>	6323 <sup>b</sup>
CB–W	3358 <sup>d</sup>	5140 <sup>c</sup>	8498 <sup>c</sup>	2984 <sup>d</sup>	4576 <sup>c</sup>	7560 <sup>c</sup>
MB–W	3284 <sup>c</sup>	5286 <sup>d</sup>	8570 <sup>c</sup>	2846 <sup>c</sup>	4780 <sup>d</sup>	7626 <sup>c</sup>
	Nutrient application rate (NAR)					
0%	1994 <sup>a</sup>	3719 <sup>a</sup>	5713 <sup>a</sup>	2022 <sup>a</sup>	3579 <sup>a</sup>	5601 <sup>a</sup>
25%	2260 <sup>b</sup>	4013 <sup>b</sup>	6273 <sup>b</sup>	2225 <sup>b</sup>	3781 <sup>b</sup>	6006 <sup>b</sup>
50%	2890 <sup>c</sup>	5034 <sup>c</sup>	7924 <sup>c</sup>	2583 <sup>c</sup>	4162 <sup>c</sup>	6745 <sup>c</sup>
75%	3466 <sup>d</sup>	5827 <sup>d</sup>	9293 <sup>d</sup>	2937 <sup>d</sup>	4538 <sup>d</sup>	7475 <sup>d</sup>
100%	3738 <sup>e</sup>	6212 <sup>e</sup>	9950 <sup>e</sup>	3097 <sup>e</sup>	4713 <sup>e</sup>	7810 <sup>e</sup>
100% + S	3931 <sup>f</sup>	6250 <sup>e</sup>	10 181 <sup>f</sup>	3127 <sup>e</sup>	4688 <sup>e</sup>	7815 <sup>e</sup>
LSD <sub>(0.05)</sub>						
CS	58	91	116	113	97	164
NP	39	79	96	65	59	101
CS × NP	86	177	215	145	133	227

<sup>†</sup>Mean values within cropping systems and nutrient application rates followed by different superscript alphabets in each column are significantly different at  $p \leq 0.05$  according to least significant difference (LSD).

\*GN–W: groundnut–wheat; GN–IG: groundnut–isabgol; GN–CP: groundnut–chickpea; CB–W: cluster bean–wheat; MB–W: mung bean–wheat.

25, 50, 75, 100% NP and 100% NP + S gave 12, 36, 59, 70 and 76% higher GY compared with no application of nutrients. The CS × NAR interaction was significant for GY in both years (Table 3). The GN–W system with 100% NP + S and 100% NP had higher GY than other systems. The SY of cropping systems varied from 3166 kg ha<sup>-1</sup> to 6134 kg ha<sup>-1</sup>. The GN–W system had significantly higher ( $p \leq 0.05$ ) SY than other cropping systems. The mean annual SY, averaged across all NAR treatments and years, was the highest for GN–W (5514 kg ha<sup>-1</sup>), which yielded 9, 12, 21 and 32% more SY compared with MB–W, CB–W, GN–CP and GN–IG systems respectively (Table 3). Averaged across cropping systems and years, application of 25, 50, 75, 100% NP produced 7, 26, 42 and 50% higher SY than 0% NP. The response to NAR was higher in 2009–2010 compared with 2010–2011. Averaged across the cropping systems, the economic yields of the cropping systems with application of 25, 50, 75, 100% NP and 100% NP + S were 2, 11, 15, 17 and 20% lower in 2010–2011 than in 2009–2010.

The BY was significantly different ( $p \leq 0.05$ ) between CS and NAR for both years (Table 3). The mean annual BY ranged between 4855 kg ha<sup>-1</sup> y<sup>-1</sup> and 9790 kg ha<sup>-1</sup> y<sup>-1</sup>. The GN–W rotation had the highest BY, and this system yielded 888, 957, 1890 and 3356 kg ha<sup>-1</sup> y<sup>-1</sup> higher BY than MB–W, CB–W, GN–CP and GN–IG systems respectively. The CB–W and MB–W systems recorded higher BY compared with the GN–IG and GN–CP systems in both years. The BY increased

linearly with an increase in NP rates. The interaction effect of CS and NAR was significant ( $p \leq 0.05$ ) for BY (Table 3). The GN–W system had higher BY compared with other systems at 75, 100% NP and 100% NP + S either year; differences in BY between GN–W and other systems were greater at higher NAR. The differences in BY between CB–W and MB–W at different -NAR were non-significant in both years.

### *Profitability*

The CC and NR varied substantially between tested crops in the present study. In the kharif season, mean annual CC was higher for groundnut (Rs. 28,186 ha<sup>-1</sup>) than mung bean (Rs. 13,334 ha<sup>-1</sup>) and cluster bean (Rs. 12,061 ha<sup>-1</sup>). In the rabi season, mean annual CC was highest for wheat (Rs. 21,155 ha<sup>-1</sup>) followed by chickpea (Rs. 15,699 ha<sup>-1</sup>) and isabgol (Rs. 11,689 ha<sup>-1</sup>) (Table 4). The mean annual NR (mean gross return (GR) – mean CC) was highest for mung bean (Rs. 34,794 ha<sup>-1</sup>) followed by groundnut (Rs. 13,932 ha<sup>-1</sup>), chickpea (Rs. 13,792 ha<sup>-1</sup>), cluster bean (Rs. 13,642 ha<sup>-1</sup>), wheat (Rs. 6103 ha<sup>-1</sup>) and isabgol (Rs. 3698 ha<sup>-1</sup>).

The CC differed considerably between the cropping systems. The mean annual CC of the cropping systems varied from Rs. 33,216 to Rs. 49,340 ha<sup>-1</sup>. The GN–W systems incurred the highest CC, and the mean annual CC for GN–CP, GN–IG, MB–W and CB–W were 10, 19, 30 and 33% respectively that of GN–W.

Cropping systems, NAR and their interaction (CS  $\times$  NAR) had significant effects ( $p \leq 0.05$ ) on returns and RI in both years (Table 5). The returns and RI for all CS were higher in 2009–2010 than 2010–2011. The GR varied significantly ( $p \leq 0.05$ ) among the cropping systems, and averaged across NAR and years, the annual mean GR was highest for MB–W (Rs. 75,561 ha<sup>-1</sup>) and this system earned Rs. 3508, 6628, 18,131 and 22,705 ha<sup>-1</sup> higher annual GR than GN–CP, GN–W, GN–IG and CB–W cropping systems respectively. The mean annual NR was highest for MB–W (Rs. 41,072 ha<sup>-1</sup>), and lowest for GN–IG (Rs. 17,556 ha<sup>-1</sup>). The MB–W system earned Rs. 13,237, 21,432, 21,478 and 23,517 ha<sup>-1</sup> higher annual NR than GN–CP, CB–W, GN–W and GN–IG systems respectively. Thus, the MB–W earned 1.5 to 2.3 times higher NR than other cropping systems. The RI of cropping systems varied from 26% to 155%, being highest for MB–W and lowest for GN–IG. The MB–W recorded significantly higher ( $p \leq 0.05$ ) RI than other systems in both years. Nutrient application improved returns and RI ( $p \leq 0.05$ ) of cropping systems. The 100% + S recorded the highest NR in 2009–2010. In 2010–2011, the 100% NP had the highest NR and RI. Application of NP @ 25, 50, 75 and 100% gave 1.1, 1.5, 2.7 and 3.9 times higher NR, respectively, compared with no application of nutrients. Averaged across years and NAR, application of 25, 50, 75 and 100% NP recorded 1.4, 2.4, 3.2 and 3.4 times higher RI than the control.

The CS  $\times$  NAR interaction was significant ( $p \leq 0.05$ ) for returns and RI in both years (Table 5). MB–W had higher GR compared with other systems at higher NP rates. The GN–W had lower GR compared with GN–CP at lower rate of NP, but at

Table 4. Cost of cultivation and gross returns (Rs. ha<sup>-1</sup>) of crops in different cropping systems during two cropping years at Bikaner, India.

Cropping system	2009–2010						2010–2011					
	Kharif			Rabi			Kharif			Rabi		
	GN	CB	MB	W	IG	CP	GN	CB	MB	W	IG	CP
	Cost of cultivation (Rs. ha <sup>-1</sup> y <sup>-1</sup> )											
GN <sup>†</sup> –W	27,667*	–	–	19,948	–	–	28,704	–	–	22,361	–	–
GN–IG	27,667	–	–	–	11,109	–	28,704	–	–	–	12,269	–
GN–CP	27,667	–	–	–	–	15,998	28,704	–	–	–	–	16,067
CB–W	–	11,470	–	19,948	–	–	–	12,652	–	22,361	–	–
MB–W	–	–	12,500	19,948	–	–	–	–	14,168	22,361	–	–
	Gross return (Rs. ha <sup>-1</sup> y <sup>-1</sup> )											
GN–W	45,491	–	–	25,594	–	–	38,001	–	–	28,781	–	–
GN–IG	45,789	–	–	–	17,155	–	38,297	–	–	–	13,618	–
GN–CP	46,440	–	–	–	–	31,124	38,684	–	–	–	–	27,857
CB–W	–	28,153	–	25,344	–	–	–	23,253	–	28,962	–	–
MB–W	–	–	57,676	25,893	–	–	–	–	38,579	28,973	–	–

<sup>†</sup>In each cropping system the first crop is grown in kharif season and the second crop is grown in rabi season.

\*Values are mean, averaged across nutrient application rate.

Selling price of groundnut, cluster bean, mung bean, wheat, chickpea and isabgol was Rs. 24.00, 18.20, 48.90, 9.80, 20.00 and 34.10 per kg respectively during 2009–2010. The selling price of groundnut, cluster bean, mung bean, wheat, chickpea and isabgol was Rs. 24.00, 18.00, 42.00, 11.80, 20.00 and 36.00 per kg respectively during 2010–2011. The selling price of straw of groundnut, cluster bean, mung bean, wheat, chickpea and isabgol was Rs. 3.00, 2.75, 1.25, 1.50, 2.00 and 0.50 per kg respectively during 2009–2010. The selling price of straw of groundnut, cluster bean, mung bean, wheat, chickpea and isabgol was Rs. 3.10, 3.00, 1.30, 2.00, 2.50 and 0.50 per kg respectively during 2010–2011.

1 US\$ = Indian Rupees (Rs.) 52.00.

Table 5. Main effects of cropping systems (CS) and nutrient application rates (NAR) on cost of cultivation (CC), gross return (GR), net return (NR) and rate on investment (RI) during two cropping years at Bikaner, India.

Treatment	2009–2010				2010–2011			
	CC (Rs. ha <sup>-1</sup> )	GR (Rs. ha <sup>-1</sup> )	NR (Rs. ha <sup>-1</sup> )	RI (%)	CC (Rs. ha <sup>-1</sup> )	GR (Rs. ha <sup>-1</sup> )	NR (Rs. ha <sup>-1</sup> )	RI (%)
Cropping system (CS)								
GN–W	47,614	71,085 <sup>c†</sup>	23,471 <sup>b</sup>	48 <sup>a</sup>	51,065	66,782 <sup>b</sup>	15,717 <sup>b</sup>	30 <sup>a</sup>
GN–IG	38,776	62,944 <sup>b</sup>	24,168 <sup>c</sup>	61 <sup>b</sup>	40,973	51,916 <sup>a</sup>	10,943 <sup>a</sup>	26 <sup>a</sup>
GN–CP	43,665	77,565 <sup>d</sup>	33,900 <sup>d</sup>	77 <sup>d</sup>	44,770	66,541 <sup>b</sup>	21,771 <sup>c</sup>	48 <sup>b</sup>
CB–W	31,418	53,497 <sup>a</sup>	22,079 <sup>a</sup>	69 <sup>c</sup>	35,014	52,215 <sup>a</sup>	17,201 <sup>b</sup>	48 <sup>b</sup>
MB–W	32,448	83,569 <sup>e</sup>	51,121 <sup>e</sup>	155 <sup>e</sup>	36,530	67,553 <sup>b</sup>	31,023 <sup>d</sup>	84 <sup>c</sup>
Nutrient application rate (NAR)								
0%	36,759	46,883 <sup>a</sup>	10,124 <sup>a</sup>	30 <sup>a</sup>	39,515	47,790 <sup>a</sup>	8275 <sup>a</sup>	23 <sup>a</sup>
25%	37,516	52,330 <sup>b</sup>	14,814 <sup>b</sup>	42 <sup>b</sup>	40,328	52,250 <sup>b</sup>	11,922 <sup>b</sup>	31 <sup>b</sup>
50%	38,273	67,470 <sup>c</sup>	29,197 <sup>c</sup>	80 <sup>c</sup>	41,140	59,186 <sup>c</sup>	18,046 <sup>c</sup>	46 <sup>c</sup>
75%	39,029	79,097 <sup>d</sup>	40,068 <sup>d</sup>	107 <sup>d</sup>	41,953	66,770 <sup>d</sup>	24,817 <sup>d</sup>	61 <sup>d</sup>
100%	39,786	84,824 <sup>e</sup>	45,038 <sup>e</sup>	117 <sup>d</sup>	42,766	69,754 <sup>e</sup>	26,988 <sup>d,e</sup>	65 <sup>e</sup>
100%+ S	41,342	87,787 <sup>f</sup>	46,445 <sup>f</sup>	116 <sup>d</sup>	44,321	70,258 <sup>e</sup>	25,937 <sup>e,f</sup>	60 <sup>d</sup>
LSD <sub>(0.05)</sub>								
CS	0.001	572	572	2	0.002	1875	1875	4
NAR	0.004	627	627	2	0.001	1411	1411	3
CS × NAR	0.009	1402	1402	4	0.002	3155	3155	8

<sup>†</sup>Mean values within cropping systems and nutrient application rates followed by different superscript alphabets in each column are significantly different at  $p \leq 0.05$  according to LSD.

GN–W: groundnut–wheat; GN–IG: groundnut–isabgol; GN–CP: groundnut–chickpea; CB–W: cluster bean–wheat; MB–W: mung bean–wheat.

higher levels of NP, the GN–W had higher ( $p \leq 0.05$ ) GR compared with GN–CP. The GN–W had lower NR compared with CB–W and GN–IG at lower NP rates, but at 100% NP rate GN–W recorded higher NR compared with the CB–W and GN–IG systems. The MB–W system recorded higher RI compared with other cropping systems at all NAR, and the differences increased at higher NAR.

#### *Water use and water use efficiencies*

The WU and WUE values were different between CS and NAR (Table 6). The WU of cropping systems varied from 672 to 945 mm  $y^{-1}$ . The GN–W had the highest WU ( $p \leq 0.05$ ), and CB–W recorded the lowest WU in both years. The CB–W, MB–W, GN–CP and GN–IG systems used 76, 78, 81 and 86% of WU used by GN–W. In general, groundnut-based cropping systems (GN–W, GN–IG and GN–CP) had higher WU compared with other cropping systems (MB–W and CB–W). Application of nutrients increased WU. The differences in WU between 0% and 50% NP were non-significant.

Water use efficiency values were higher in 2009–2010 compared with 2010–2011 (Table 6). The  $WUE_{GY}$  of cropping systems varied from 2.3 to 4.7 kg  $ha^{-1}$  mm $^{-1}$ . Averaged across NAR and years, the CB–W system had the highest  $WUE_{GY}$  (4.6 kg  $ha^{-1}$  mm $^{-1}$ ), and GN–IG had the lowest  $WUE_{GY}$  (2.4 kg  $ha^{-1}$  mm $^{-1}$ ).  $WUE_{BY}$  varied from 6.5 to 11.3 kg  $ha^{-1}$  mm $^{-1}$ . The CB–W and MB–W systems had 1.2 times higher  $WUE_{BY}$  compared with the GN–W system. The MB–W and CB–W systems had higher ( $p \leq 0.05$ )  $WUE_{BY}$  compared with other systems in both years (Table 4). The MB–W and CB–W systems were more water use efficient systems in term of yields ( $WUE_{GY}$  and  $WUE_{BY}$ ) compared with the GN–W system. The MB–W had higher ( $p \leq 0.05$ )  $WUE_R$  compared with other systems in both years. Averaged across NAR and years, MB–W recorded 1.5, 2.0, 2.5 and 2.7 times higher  $WUE_R$  compared with GN–CP, CB–W, GN–IG and GN–W respectively.

Nutrient application showed significant improvement ( $p \leq 0.05$ ) in WUEs in both years. In 2009–2010, WUEs ( $WUE_{GY}$ ,  $WUE_{ABY}$  and  $WUE_R$ ) increased with an increase in NAR and 100% NP + S had higher WUEs compared with all other NAR (Table 6). Averaged across CS and years, the application of 100% NP recorded 66% and 41% higher  $WUE_G$  and  $WUE_{BY}$ , respectively, than 0% NP. The effect of NAR was more pronounced on  $WUE_R$  than effects on  $WUE_{GY}$  and  $WUE_{BY}$ ; and application of 100% NAR recorded 3.4, 2.5 and 1.5 times higher  $WUE_R$  compared with 0, 25 and 50% NAR.

The CS  $\times$  NAR interaction was detected significant for WUEs (Table 6). The CB–W system had higher WUEs compared with other systems at all NAR tested. At 0% NAR, the differences in  $WUE_{GY}$  between MB–W, GN–W and GN–CP were non-significant. The GN–W had lower  $WUE_{GY}$  and  $WUE_{BY}$  compared with GN–CP at 0, 25 and 50% NAR, however at higher NAR (75, 100, 100% NP + S) the GN–W system recorded significantly higher  $WUE_{GY}$  and  $WUE_{BY}$  compared with GN–IG in both years. The GN–IG system had the lowest  $WUE_{GY}$  compared with other cropping systems at all NAR.

Table 6. Main effects of cropping systems (CS) and nutrient application rates (NAR) on water use (WU), water use efficiency (WUE) in terms of grain yield (WUE<sub>GY</sub>), biomass yield (WUE<sub>BY</sub>) and net return (WUE<sub>R</sub>) during two cropping years at Bikaner, India.

Treatment	2009–2010				2010–2011			
	WU (mm)	WUE <sub>GY</sub> (kg ha <sup>-1</sup> mm <sup>-1</sup> )	WUE <sub>BY</sub> (kg ha <sup>-1</sup> mm <sup>-1</sup> )	WUE <sub>R</sub> (Rs. ha <sup>-1</sup> mm <sup>-1</sup> )	WU (mm)	WUE <sub>GY</sub> (kg ha <sup>-1</sup> mm <sup>-1</sup> )	WUE <sub>BY</sub> (kg ha <sup>-1</sup> mm <sup>-1</sup> )	WUE <sub>R</sub> (Rs. ha <sup>-1</sup> mm <sup>-1</sup> )
	Cropping system (CS)							
GN–W	945 <sup>d†</sup>	3.8 <sup>c</sup>	9.8 <sup>c</sup>	24.4 <sup>a</sup>	877 <sup>c</sup>	3.8 <sup>b</sup>	9.3 <sup>b</sup>	17.9 <sup>b</sup>
GN–IG	804 <sup>c</sup>	2.5 <sup>a</sup>	7.4 <sup>a</sup>	30.1 <sup>b</sup>	747 <sup>b</sup>	2.3 <sup>a</sup>	6.5 <sup>a</sup>	14.6 <sup>a</sup>
GN–CP	795 <sup>c</sup>	3.7 <sup>b</sup>	9.4 <sup>b</sup>	41.2 <sup>c</sup>	682 <sup>a</sup>	3.7 <sup>b</sup>	9.4 <sup>b</sup>	31.7 <sup>d</sup>
CB–W	711 <sup>a</sup>	4.7 <sup>c</sup>	11.2 <sup>c</sup>	30.2 <sup>b</sup>	672 <sup>a</sup>	4.4 <sup>c</sup>	11.2 <sup>c</sup>	25.6 <sup>c</sup>
MB–W	743 <sup>b</sup>	4.4 <sup>d</sup>	10.8 <sup>d</sup>	67.1 <sup>c</sup>	677 <sup>a</sup>	4.2 <sup>d</sup>	11.3 <sup>c</sup>	45.7 <sup>e</sup>
	Nutrient application rate (NAR)							
0%	792 <sup>a</sup>	2.5 <sup>a</sup>	7.3 <sup>a</sup>	14.1 <sup>a</sup>	708 <sup>a</sup>	2.9 <sup>a</sup>	8.2 <sup>a</sup>	12.8 <sup>a</sup>
25%	794 <sup>a,b</sup>	2.9 <sup>b</sup>	7.9 <sup>b</sup>	19.8 <sup>b</sup>	730 <sup>a,b</sup>	3.1 <sup>a</sup>	8.3 <sup>a</sup>	17.1 <sup>b</sup>
50%	798 <sup>a,b,c</sup>	3.6 <sup>c</sup>	9.7 <sup>c</sup>	37.6 <sup>c</sup>	734 <sup>b</sup>	3.5 <sup>b</sup>	9.3 <sup>b</sup>	25.3 <sup>c</sup>
75%	802 <sup>b,c</sup>	4.4 <sup>d</sup>	10.8 <sup>d</sup>	49.9 <sup>d</sup>	737 <sup>b</sup>	4.0 <sup>c</sup>	10.2 <sup>c</sup>	34.5 <sup>d</sup>
100%	806 <sup>c</sup>	4.7 <sup>e</sup>	11.3 <sup>c</sup>	54.2 <sup>c</sup>	739 <sup>b</sup>	4.2 <sup>d</sup>	10.6 <sup>c</sup>	37.2 <sup>d,e</sup>
100%+ S	806 <sup>b,c</sup>	4.9 <sup>f</sup>	11.4 <sup>e</sup>	55.9 <sup>f</sup>	739 <sup>b</sup>	4.2 <sup>d</sup>	10.6 <sup>c</sup>	35.6 <sup>c</sup>
	LSD <sub>(0.05)</sub>							
CS	9.1	0.1	0.3	0.8	19.9	0.2	0.5	2.7
NAR	8.6	0.1	0.2	1.0	24.8	0.2	0.5	2.2
CS × NAR	NS	0.2	0.4	2.2	NS	0.4	1.1	4.9

<sup>†</sup>Mean values within cropping systems and nutrient application rates followed by different superscript alphabets in each column are significantly different at  $p \leq 0.05$  according to LSD.

GN–W: groundnut–wheat; GN–IG: groundnut–isabgol; GN–CP: groundnut–chickpea; CB–W: cluster bean–wheat; MB–W: mung bean–wheat.

## DISCUSSION

An appropriate cropping system is critical to maintaining/enhancing agronomic sustainability (Joshi *et al.*, 2009). Numerous studies have demonstrated that diversification of cropping systems improves productivity and profitability (Gangwar *et al.* 1999; Singh *et al.*, 2008b); but the choices to be made require integrated assessment of various cropping systems (Biswas *et al.*, 2006; Gangwar and Prasad, 2005). In our study area, where GN–W is a common cropping sequence, the incorporation of alternative crops, such as mung bean, cluster bean, isabgol and chickpea, into the rotation was studied. Mung bean, cluster bean and chickpea were chosen for their lower water requirement, and isabgol for its potential in the medicinal market. Relative performances of five cropping systems were assessed in terms of productivity, profitability and WUEs.

In this study, yields of crops were higher in 2009–2010 compared with 2010–2011 (Table 2). Year-to-year variability in crop yields is mainly influenced by environmental factors, pest pressures and management (Grover *et al.*, 2009). Higher yield of crops in 2009–2010 than in 2010–2011 observed in the present study might have been due to longer crop duration in 2009–2010 compared with that in 2010–2011 (Table 2). Furthermore, lower yield of kharif season crops in 2010–2011 could possibly be attributed to higher pest and disease incidences due to higher relative humidity during post-flowering stage (Figure 1) in 2010–2011. Rabi season crops experienced heat stress during the later stage during 2010–2011 (Figure 1), which probably reduced yields of crop in the rabi season of 2010–2011 than in 2009–2010. Decrease in yields of crops, including wheat and chickpea, due to heat stress has been reported in other studies (Sharma *et al.*, 2005; Summerfield *et al.*, 1984). Temporal variability of yield of crops measured in terms of coefficient of variation (CV) ranged from a low of 5% for wheat to a high of 25% for mung bean. Among the studied crops, yield reduction in 2010–2011 compared with 2009–2010 was highest for mung bean among the kharif season crops, and for isabgol among the rabi season crops. These results indicate relatively higher risk associated with the cultivation of mung bean and isabgol compared with other crops. Producers who are generally risk averse will typically avoid crops that have higher production variability. The high risk associated with mung bean and isabgol is a possible explanation for avoiding their cultivation by producers in the study region.

In terms of yields (both GY and BY), GN–W was the most productive system in the present study (Table 3). Higher BY of GN–W is due to higher BY of both groundnut and wheat than other crops in respective seasons (Table 2). Higher BY of groundnut and wheat might be explained by longer duration coupled with higher radiation use efficiency (RUE) compared with other crops in respective seasons. Higher BY of systems involving wheat (GN–W, MB–W and CB–W) compared with the systems that involve chickpea and isabgol (GN–IG and GN–CP) observed in the present study might be explained by the higher BY of wheat relative to chickpea and isabgol. In the present study, GN–W yielded the highest GY. This could possibly be attributed to higher BY and HI of groundnut and wheat compared with other crops in respective

seasons. Better BY and HI for wheat relative to chickpea and isabgol is a possible explanation for higher GY of cropping systems involving wheat (GN–W, CB–W and MB–W) compared with the systems that not included wheat (GN–CP and GN–IG). Our finding that GN–W gave the highest yields is consistent with the studies of Ghosh *et al.* (2003) and Jat *et al.* (2011). Ghosh *et al.* (2003) found that GN–W gave 0.4 to 0.8 t ha<sup>-1</sup> higher GY than the GN–GN, GN–CP, GN–M (mustard) and GN–SF (sunflower) systems in Gujarat, India. Jat *et al.* (2011) showed that GN–W produced 2.4, 2.6 and 3.0 times higher GY than the PM (pearl millet)–CP, GN–M and S (sorghum)–CP systems, respectively, in Rajasthan, India.

Mixed crop–livestock systems are the dominant forms of agricultural production in many regions of the world. Crop residues constitute 40–60% of animals' total dry matter (DM) intake in Asia and Africa (Rao and Hall, 2003). Therefore, yield and quality of crop residues are important criteria used to assess the performance of cropping systems. Groundnut straw contains 94% DM, and 9% crude protein (CP). The cluster bean straw contains 93% DM, and 7% CP (Gupta *et al.*, 2012). Mung bean straw contains 88% DM and 10% CP (Khatik *et al.*, 2007), and is generally fed after mixing with straw of other palatable crops. Wheat straw is the most common source of roughage for cattle, and it contains 90% DM and 3% CP (Ranjhan, 1991). Chickpea straw contains 90% DM and 10.5% protein (Ranjhan, 1991), and is a common feed for camel, sheep and goat. Considering the feeding value of straw (excluding SY of isabgol as it is not used as fodder), GN–W yielded the greatest quantity of fodder followed by MB–W, CB–W, GN–CP and GN–IG. Considering the quality of fodder in terms of CP (calculated by multiplying CP content of straw with SY of respective crops), mean annual CP yields were highest for GN–CP, intermediate for GN–W and MB–W, and lower for CB–W and GN–IG. Therefore, GN–W, GN–CP, MB–W and CB–W were better systems for livestock feeding considering both DM and CP yields. GN–IG was the least efficient system with respect to dry matter and protein yields for feeding livestock.

Our results demonstrated that application of nutrients increased yields of cropping systems (Table 3, Figure 2). This could possibly be attributed to increased availability of nutrients to crops due to application of fertilizers. Our findings are in agreement with other studies where application of 100% NP increased the productivity of pearl millet–cumin, pearl millet–Indian mustard and fallow–wheat (Yadav and Poonia, 1996), CB–M and CB–IG (Saxena *et al.*, 2003) cropping systems in Rajasthan, India. Our study showed that S-application with 100% NP gave higher yields than 100% NP. Dayanand and Meena (2002), Sharma and Singh (2005) and Singh *et al.* (2005) have demonstrated that S-application increased crops (cluster bean, wheat and groundnut) yields in the arid regions of Rajasthan. Furthermore, yield and return responses to fertilizer application was lower in 2010–2011 compared with 2009–2010. The lower responses in 2010–2011 might be attributed to unfavourable weather conditions in this year compared with 2009–2010. In addition, inter-annual variability of responses to nutrient application increased with an increase in NAR. This indicates risk associated with use of high fertilizer rates, and explains reason for avoiding use of higher rates of fertilizers by producers. Decision-making in a risky



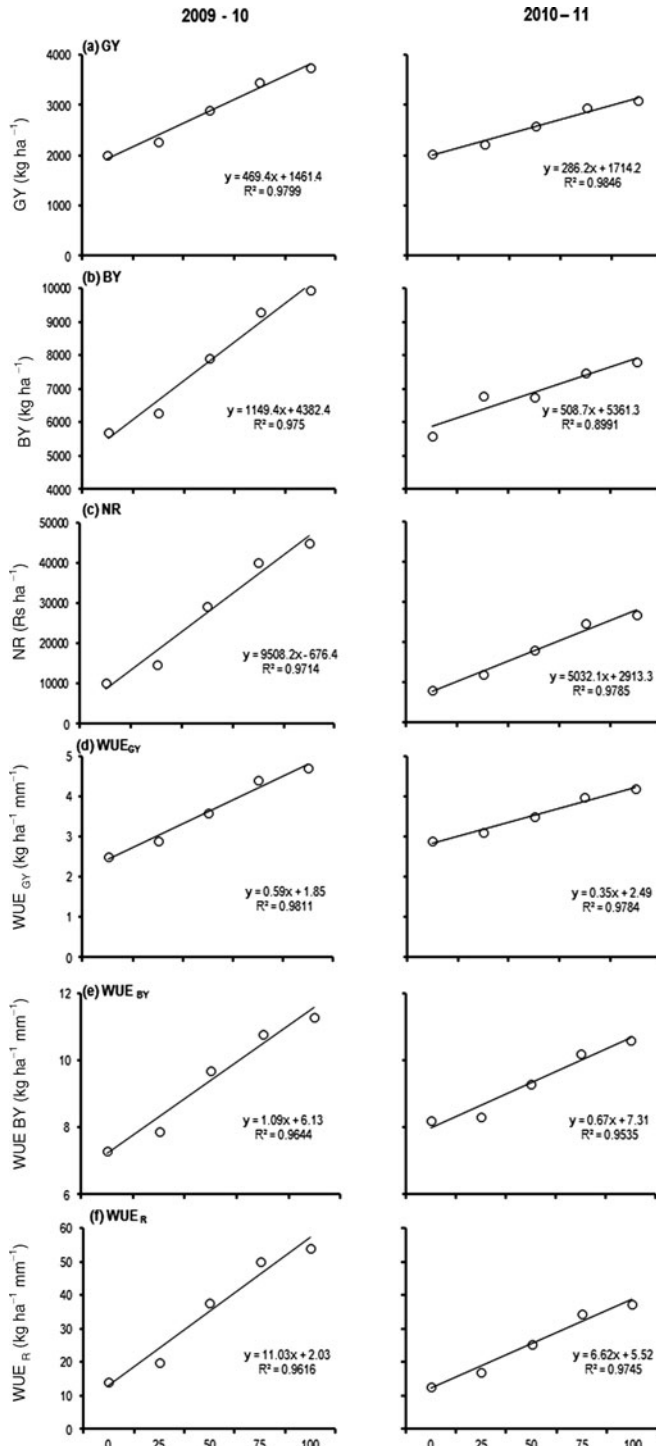


Figure 2. Response functions of (a) grain yields, (b) biomass yield, (c) net returns, (d) WUE in terms of grain yield, (e) WUE in terms of biomass yield and (f) WUE in terms of return of cropping systems to NAR at Bikaner, India.

or uncertain environment usually requires making a trade-off between increases in net returns and increases in income variability (Zentner and Campbell, 1988). Often producers may increase their expected net earnings by choosing higher fertilizer application rates, but only at the expense of having accepted higher income variability or financial risk. The extent of this trade-off depends on the risk preference held by individual producers. Producers who are risk averse will typically avoid high fertilizer rates that provide not only higher net returns but also higher income variability.

In the present study, differences in profitability of cropping systems reflected variations in differences between GR (depending on yield and selling prices) and CC (depending on cultural and input requirements) among component crops of the cropping systems. Groundnut incurred the greatest CC among the kharif season crops due to higher labour, irrigation, seed and plant protection chemical requirements relative to cluster bean and mung bean (Table 4). Wheat had the highest CC among the rabi season crops, mainly due to higher labour and irrigation costs compared with chickpea and isabgol. Costs of cultivation for the systems that included GN (GN-W, GN-CP and GN-IG) tended to be higher than for systems that included cluster bean (CB-W) and mung bean (MB-W) (Table 5) due to higher CC of groundnut (Table 4). Similarly, CC for groundnut-based systems that included wheat (GN-W) is higher than the systems that included chickpea (GN-CP) and isabgol (GN-IG) due to higher CC of wheat. This indicates that substitution of groundnut by cluster bean and mung bean, and that of wheat by chickpea and isabgol, requires fewer resource expenditures (labour, seed and pesticides).

In the present study, MB-W was the most profitable system, and it earned the highest NR and RI (Table 5). The Highest profit for MB-W cropping systems is attributed to higher selling prices and lower CC of mung bean than groundnut and cluster bean coupled with better yield of wheat than chickpea and isabgol. In spite of 12% less GY, MB-W earned two-fold higher NR than GN-W due to ~30% less CC and ~60% higher selling prices of mung bean compared with groundnut. These results are in contrast to the study by Jat *et al.* (2011), who showed that GN-W was profitable than MB-W. This difference from earlier report is mainly due to higher selling price of mung bean coupled with higher CC of groundnut than mung bean in the present study. In spite of ~33% less CC for CB-W than GN-W, both these systems earned almost similar NR due to ~10% less yield and 25% less selling price for cluster bean than for groundnut. In spite of better GY, GN-W was less profitable than GN-CP, and this is attributed to lower CC (~10% less than wheat) and higher selling price (~45% higher than wheat) of chickpea than wheat. Notwithstanding better selling price and lower CC of isabgol, its extremely low GY compared with wheat (~47% less than wheat) is responsible for lower profitability of GN-IG than GN-W. We found that nutrient applications increased profitability of the cropping systems (Table 5), which might be attributed to more increase in returns (due to higher yields) relative to cost incurred in nutrient applications. Increase in returns of crops due to fertilizer applications in arid region of India have been reported in other studies (Rathore *et al.*, 2007; Singh *et al.*, 2008a).

Changes in expected product prices influenced level of net earnings of the cropping systems (Table 7). The net returns of groundnut -based cropping systems were more sensitive to change in price of groundnut than change in prices of the rabi season crops (wheat, isabgol and chickpea). The change in prices for groundnut had the highest effects on net earnings of GN-IG followed by the GN-W and GN-CP cropping systems, directly reflecting differences in yields of the rabi season crops. The GN-CP remained the most profitable among groundnut-based cropping systems at both lower prices and higher prices of groundnut. The MB-W system remained the most profitable cropping system at most of the expected price change scenarios, and its net earnings were more sensitive to change in price for mung bean than for change of prices for wheat. It was profitable to grow groundnut than mung bean when the ratio of groundnut price to mung bean price exceeded 0.8. Producers will find the GN-W rotation economically attractive than MB-W when ratio of groundnut price to mung bean price rose up to 0.8, possibly because of higher groundnut or lower mung bean prices. It was profitable to substitute cluster bean for mung bean when the cluster bean/mung bean price ratio exceeded 0.8; and at this price ratio CB-W was the most profitable cropping system. The price ratios of cluster bean to mung bean ranged from 0.4 to 1.1 for 2001–2010, thus indicating that growers will find cluster bean more profitable under higher cluster bean or lower mung bean prices. It was profitable to grow wheat than chickpea when the ratio of wheat price to chickpea price exceeded 0.7. It was profitable to produce isabgol than wheat and chickpea when the isabgol/wheat and isabgol/chickpea price ratios were greater than 5.4 and 2.9 respectively. The recent historical (2001–2010) isabgol/wheat and isabgol/chickpea price ratios have ranged from 3.1 to 3.9 and 1.5 to 2.0 respectively, thus indicating that area producers will not likely find isabgol rotation economically attractive in foreseeable future, except possibly by those with a specialized need for isabgol (e.g. pharmaceutical industry).

We explored the profitability of cropping systems under irrigation water pricing. The 'in-kind contract' is a common water pricing system, and 20 to 40% of crop output has been charged as water price in the study region. At water price @ 20% of GR of crops, all cropping systems remained profitable (NR ranged from Rs. 6128 to 25,820 ha<sup>-1</sup>); and at this price of water, reduction in NR compared with free water was higher (65–70%) for GN-W and GN-IG, intermediate (50–55%) for GN-CP and CB-W and lowest (37%) for MB-W. At water price @ 30% of GR of crops, the MB-W system was non-profitable. All the systems lost returns and were non-profitable when water is charged @ 40% of GR of crops. Our analysis indicated that area producers would find the MB-W, CB-W and GN-CP rotations economically attractive than GN-W and GN-IG under water pricing scenarios.

Differences observed in WU of cropping systems reflected differences in WU of component crops of the cropping systems. Higher WU for groundnut observed in the present study might be attributed to longer duration and early planting time during the period of higher evaporative demand than other crops in the kharif season. Other studies demonstrated that WU for groundnut was higher (716–796 mm; Patel *et al.*, 2008) than cluster bean (425–654 mm; Rao and Singh, 1998), and mung bean

Table 7. Effects of price change on mean net returns of cropping systems at Bikaner, India.

Net Return (Rs. (,000) ha <sup>-1</sup> )																			
Groundnut–Wheat				Groundnut–Isabgol				Groundnut–Chickpea				Cluster bean–Wheat				Mung bean–Wheat			
W			IG			CP			W			W							
GN**	Base	Low	High	GN	Base	Low	High	GN	Base	Low	High	CB	Base	Low	High	MB	Base	Low	High
Base	20	14	26	Base	18	13	22	Base	28	21	35	Base	20	14	26	Base	41	35	47
Low	9	3	15	Low	6	2	11	Low	17	10	24	Low	13	6	19	Low	18	12	24
High*	31	25	37	High	29	24	33	High	39	32	46	High	27	21	33	High	64	58	70

\*High prices reflect two standard deviations above the respective base price of crops, and low prices reflect two standard deviations below the respective base prices of crops.

\*\*GN: groundnut; W: wheat; IG: isabgol; CP: chickpea; CB: cluster bean; MB: mung bean.

(293–404 mm; Rao, 2009). Higher WU of wheat compared with isabgol and chickpea is possibly explained by longer duration of wheat. The highest WU for GN–W observed in the present study is attributed to higher WU of groundnut and wheat compared with other crops in respective seasons. Considering WUE in yield (GY and BY) terms, the CB–W and MB–W were more water use efficient systems than the GN–W system (Table 6). The following three principal explanations likely contributed to higher WUEs in terms of yields for mung bean and cluster bean compared with groundnut in the present study: (i) The short duration of mung bean and cluster bean decreases the total ET; (ii) they develop canopy quickly than groundnut, leading to decreased share of evaporation (E) in the total ET, and hence increased share of transpiration (T) in total ET and (iii) they produced higher grain and biomass yields per day compared with groundnut. GN–IG was the least efficient system with respect to WUEs in terms of yields. Extremely low yields of isabgol might be responsible for the lowest WUEs of the GN–IG system. In contrast to yields and WUE in yield terms, the MB–W system was the most water use efficient system in economic terms ( $WUE_R$ ; returns per unit of water used). The higher  $WUE_R$  of MB–W is attributed to lower WU and higher NR (due to higher selling price and lower CC) of mung bean than cluster bean and groundnut. In spite of the highest selling price for isabgol, the GN–IG was the least water use efficient system in terms of  $WUE_R$  due to the lowest GY of isabgol in the present study. Nutrient application improved WUE of all the cropping systems (Table 6) in the present study. Our findings are consistent with the studies of Garg *et al.* (1993), Rathore *et al.* (2007) and Singh *et al.* (2010), who found that nutrient application improved WUEs of crops in arid region. Nutrient application has been shown to increase the share of T in total ET via early canopy growth, and thus improves yield and WUE without affecting total ET to any great extent (Gregory *et al.*, 1984).

Our results indicate that tested cropping systems varied significantly in terms of productivity, profitability and WUEs, and support our hypothesis that diversified crop rotations have higher returns and WUEs than the GN–W system. At current price levels, the MB–W system with the highest profits and  $WUE_R$ , and the second highest  $WUE_{GY}$ ,  $WUE_{BY}$  and yields (BY) seems to be the most efficient system compared with other systems for hot arid region of India.

#### CONCLUSIONS

The tested cropping systems varied considerably with respect to agronomic, economic and water use performances. Under the seasonal conditions and crop product prices that occurred during this experiment, the substitution of groundnut by short duration legumes, i.e. mung bean and cluster bean, resulted in higher returns and WUEs. The MB–W rotation resulted in the highest returns and WUEs due to lower cost of cultivation, better selling prices and less water use by mung bean than groundnut. Lower production cost and water use of mung bean and cluster bean compared with groundnut has an extra appeal to producers in that it entails low capital and water requirements. Producers must remain flexible in their choice of crop so as to

respond appropriately to changing market conditions. It was generally more profitable to produce groundnut and cluster bean than mung bean when the groundnut/mung bean and cluster bean/mung bean price ratios exceeded 0.8. Further, it was more profitable to produce wheat than chickpea when the wheat/chickpea price ratio exceeded 0.7. Enhanced yields and profits under the application of 100% NP is a pointer to the superiority of 100% recommended dose of N and P over other rates of nutrient application. Our results suggest that substitution of groundnut-based rotation by short duration, low input (water, nutrient and labour) requiring crops, i.e. mung bean- and cluster bean-based rotations with 100% NP be adopted in this environment to get higher returns and WUE. Long-term studies may be further needed to ascertain performances of various cropping systems with regard to soil quality and returns under price fluctuations.

*Acknowledgements.* Bherun Singh and other staff attached to the Regional Research Station of the CAZRI assisted during the field phase of this research. The project was funded by the Ministry of Water Resources, Government of India.

#### REFERENCES

- Biswas, B., Ghosh, D. C., Dasgupta, M., Trivedi, K. N., Timsina, J. and Doberman, A. (2006). Integrated assessment of cropping systems in the eastern Indo-Gangetic plain. *Field Crops Research* 99:35–47.
- Cai, X. and Rosegrant, M. W. (2003). World water productivity: current situation and future options. In *Water Productivity in Agriculture: Limit and Opportunities for Improvement*, 163–178 (Eds J. W. Kijne, R. Barker and R. Molden). Colombo, Sri Lanka: IWMI.
- Dayanand, and Meena, N. L. (2002). Growth, yield and economics of groundnut (*Arachis hypogea*) as influenced by intercrop and sulphur application. *Indian Journal of Agronomy* 47:345–349.
- Faroda, A. S., Joshi, N. L., Singh, R. and Saxena, A. (2007). Resource management for sustainable crop production in arid zone – a review. *Indian Journal of Agronomy* 52:181–193.
- Gangwar, B., Katyay, V. and Patel, M. M. (1999). Productivity, stability and efficiency of various crop sequences in arid ecosystem. *Journal of Farming Systems Research and Development* 5:1–9.
- Gangwar, B. and Prasad, K. (2005). Cropping system management for mitigation of second-generation problems in agriculture. *Indian Journal of Agricultural Sciences* 75:65–78.
- Garg, B. K., Kathju, S., Vyas, S. P. and Lahiri, A. N. (1993). Effect of plant density and soil fertility on pearl millet under drought and good rainfall situations. *Annals of Arid Zone* 32:13–20.
- Ghosh, P. K., Dayal, D., Mandal, K. G., Wanjari, R. H. and Hati, K. M. (2003). Optimization of fertilizer schedules in fallow and groundnut-based cropping systems and an assessment of system sustainability. *Field Crops Research* 80:83–98.
- Gregory, P. J., Shepherd, K. D. and Cooper, P. J. (1984). Effect of fertilizer on root growth and water use of barley in northern Syria. *Journal of Agricultural Science (Cambridge)* 103:129–438.
- Grover, K. K., Karsten, H. D. and Roth, G. W. 2009. Corn grain yields and yield stability in four long-term cropping systems. *Agronomy Journal* 101:940–946.
- Gupta, L., Roy, A. K., Tiwari, G., Dhuria, R. and Garg, R. (2012). Effect of feeding different proportion of groundnut haulms (*Arachis hypogea*) and clusterbean (*Cyamopsis tetragonoloba*) on nutrient utilization and serum biochemical parameters in dromedary camels. *Tropical Animal Health Production* 44:1689–1695.
- Howell, T. (2001). Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal* 93:181–189.
- Jat, H. S., Meena, L. R., Mann, J. S., Chand, R., Chander, S. and Sharma, S. C. (2011). Relative efficiency of different cropping sequences in a farmers participatory research programme in semi-arid agro-ecosystem of Rajasthan. *Indian Journal of Agronomy* 56:321–327.
- Joshi, N. L., Dayal, D., Saxena, A., Kumawat, R. N., Singh, I., Bhati, D. S., Burman, U., Rao, S. S., Regar, P. L., Tanwar, S. P. S., Singh, H. P. and Singh, A. K. (2009). Agronomic management for sustainable crop production

- in arid environment. In *Trends in Arid Zone Research in India*, 278–323 (Eds A. Kar, B. K. Garg, M. P. Singh and S. Kathju). Jodhpur, India: CAZRI.
- Joshi, N. L. and Saxena, A. (1997). Management of irrigated crops in Indian arid ecosystem. In *Desertification Control in the Arid Ecosystem of India for Sustainable Development*, 308–316 (Eds S. Singh and A. Kar). Bikaner, India: Agro-Botanical.
- Kathju, S., Joshi, N. L., Rao, and A. V. Parveen Kumar (1998). Arable crop production. In *Fifty Years of Arid Zone Research in India*, 215–252 (Eds A. S. Faroda and M. Singh). Jodhpur, India: CAZRI.
- Khatik, K. L., Vaishnava, C. S. and Gupta, L. (2007). Nutritional evaluation of green gram (*Vigna radiata* L.) straw in sheep and goats. *Indian Journal of Small Ruminants* 13:196–198.
- Molden, D. (2007). *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London/Colombo: Earth Scan/IWMI.
- Patel, G. N., Patel, P. T. and Patel, P. H. (2008). Yield, water use efficiency and moisture extraction pattern of summer groundnut as influenced by irrigation schedules, sulfur levels and sources. *Journal of SAT Agricultural Research* 6: 1–4.
- Peterson, G. A., Schlegel, A. J., Tanaka, D. L. and Jones, O. R. (1996). Precipitation use efficiency as affected by cropping and tillage systems. *Journal of Production Agriculture* 9:180–186.
- Ranjhan, S. K. (1991). *Chemical Composition and Nutritive Value of Indian Feeds and Feeding of Farm Animals*. New Delhi, India: Indian Council of Agricultural Research, 132.
- Rao, A. S. (2009). Climate variability and crop production in arid western Rajasthan. In *Trends in Arid Zone Research in India*, 48–61 (Eds A. Kar, B. K. Garg, M. P. Singh and S. Kathju). Jodhpur, India: CAZRI.
- Rao, P. P. and Hall, A. J. (2003). Importance of crop residues in crop-livestock systems in India and farmers' perceptions of fodder quality in coarse cereals. *Field Crops Research* 84:189–198.
- Rao, A. S. and Singh, R. S. (1998). Climatic features and crop production. In *Fifty Years of Arid Zone Research in India*, 17–38 (Eds A. S. Faroda and M. Singh). Jodhpur, India: CAZRI.
- Rao, A. V., Tarafdar, J. C., Sharma, S. K., Kumar, P. and Aggarwal, R. K. (1995). Influence of cropping systems on soil biochemical properties in an arid rain-fed environment. *Journal of Arid Environments* 31:237–244.
- Rathore, M. S. (2003) *Groundwater Exploration and Augmentation Efforts in Rajasthan – A Review*. Jaipur, India: Institute of Development Studies.
- Rathore, V. S., Singh, J. P. and Beniwal, R. K. (2009). Rainfed farming systems of hyper arid north western Rajasthan: an analysis. *Annals of Arid Zone* 48:125–131.
- Rathore, V. S., Singh, J. P., Soni, M. L., Yadava, N. D. and Beniwal, R. K. (2007). Productivity, quality and resource utilization by clusterbean (*Cyamopsis tetragonoloba*) as influenced by nutrient management. *Indian Journal of Agronomy* 52:243–246.
- Rathore, V. S., Singh, J. P., Soni, M. L., Yadava, N. D. and Beniwal, R. K. (2010). Evaluation of irrigated farming systems of hot arid region of north-western Rajasthan. *Annals of Arid Zone* 49:39–45.
- Riedell, W. E., Schumacher, T. E., Clay, S. A., Ellsbury, M. M., Pravecek, M. and Evenson, Pd. (1998). Corn and soil fertility response to crop rotation with low, medium or high inputs. *Crop Science* 38:427–433.
- Rosegrant, M. W., Ringler, C. and Zhu, T. (2009). Water for agriculture: maintaining food security under growing scarcity. *Annual Review of Environment and Resources* 34:205–222.
- Saxena, A., Singh, D. V. and Joshi, N. L. (1997). Effects of tillage and cropping systems on soil moisture balance and pearl millet yield. *Journal of Agronomy and Crop Science* 178:251–257.
- Saxena, A., Singh, Y. V., Singh, D. V. and Patidar, M. (2003). Production potential and economics of clusterbean (*Cyamopsis tetragonoloba*)-based cropping systems for arid regions. *Indian Journal of Agronomy* 48:27–29.
- Sharma, K. D., Pannu, R. K. and Behl, R. K. (2005). Effect of early and terminal heat stress on biomass partitioning, chlorophyll stability and yield of different wheat genotypes. In *Proceedings of International Conference on Sustainable Crop Production in Stress Environments: Management and Genetic Options*, 87–94 (Ed. K. B. Singh). Jabalpur, India: Jawaharlal Krishi VishavVidhalaya.
- Sharma, O. P. and Singh, G. D. (2005). Effect of sulphur in conjunction with growth substances on productivity of clusterbean (*Cyamopsis tetragonoloba*) and their residual effect on barley (*Hordeum vulgare*). *Indian Journal of Agronomy* 50:16–18.
- Singh, S., Gill, O. P., Nag, A. K. and Singh, K. P. (2008b). Diversification of crop sequences in semi-arid eastern plain zone of Rajasthan. *Journal of Farming System Research and Development* 14:42–45.
- Singh, Y. V., Rao, S. S. and Regar, P. L. (2010). Deficit irrigation and nitrogen effects on seed cotton yield, water productivity and yield response factor in shallow soils of semi-arid environment. *Agricultural Water Management* 97:965–970.

- Singh, Y. P., Sharma, S. C. and Man, J. S. (2005). Effect of sulphur on yield and its uptake in groundnut (*Arachis hypogaea*) and their residual effect on succeeding wheat (*Triticum aestivum*). *Indian Journal of Agronomy* 50:116–118.
- Singh, R., Singh, B. and Patidar, M. (2008a). Effect of preceding crops and nutrient management on productivity of wheat (*Triticum aestivum*)-based cropping system in arid region. *Indian Journal of Agronomy* 53:267–272.
- Summerfield, R. J., Hadley, P., Roberts, E. H., Minchin, F. R. and Rawsthane, S. (1984). Sensitivity of chickpea (*Cicer arietinum* L.) to hot temperatures during the reproductive period. *Experimental Agriculture* 20:77–93.
- Yadav, R. S. and Poonia, B. L. (1996). Effect of fertilizers on the production potential of different crop sequences in arid regions. *Indian Journal of Agronomy* 41:199–204.
- Zentner, R. P., Campbell, C. A., Selles, F., Jefferson, P. G., Lemke, R., McConkey, B. G., Fernandez, M. R., Hamel, C., Gan, Y. and Thomas, A. G. (2006). Effect of fallow frequency, flexible rotations, legume green manure, and wheat class on the economics of wheat production in the Brown soil zone. *Canadian Journal of Plant Science* 86:413–423.
- Zentner, R. P. and Campbell, C. A. (1988). First 18 years of a long-term crop rotation study in southwestern Saskatchewan – yields, grain protein, and economic performance. *Canadian Journal of Plant Science* 68:1–21.