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Cotton (*Gossypium hirsutum*) establishment methods based system-intensification: Effects on *Bt* cotton growth, weed suppression, system crop and water productivity, system-profitability and land–use efficiency in Indo–Gangetic plains region

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ABSTRACT

A field experiment was conducted at IARI, New Delhi during 2014-15 and 2015-16 to study the effect of *Bt* cotton (*Gossypium hirsutum* L.) establishment methods (CEMs) and planting geometry on plant growth, yield and weed suppression behaviour in *Bt* cotton vis-à-vis system productivity, profitability, water-productivity, production-efficiency, economic-efficiency and land use efficiency. The experiment was laid out in split-plot-design with four replications comprising two CEMs [transplanted-cotton (TPC) and direct-seeded-cotton (DSC)] and three planting geometries/plant densities [(90×60 cm (18,518 plants/ha); 75 × 45 cm (29629 plants/ha) and 60×45 cm (37,037 plants/ha)] and four cropping systems viz. TPC−wheat−mungbean; TPC−onion−fodder cowpea + maize; DSC−wheat; and DSC−onion cropping system under above two CEMs. Among CEMs, the DSC-cotton resulted in higher plant growth though the seed yield and lint yield were respectively higher by ~9.54% and ~15% under TPC-cotton over DSC-cotton due to better plant stand in TPC–CEM. On an average, the significantly highest system productivity in terms of seed-cotton-equivalent-yield (SCEY) was registered in TPC−wheat−mungbean/TPC−onion−fodder cowpea + maize cropping systems (mean of both systems) during 2014–15 (6.75 t/ha) and 2015–16 (6.96 t/ha), respectively. In general, the legume-intensification in TPC–based cropping systems exhibited about 25 to 27% higher system yield (SCEY) over DSC–based cropping systems. The TPC–based cropping systems exhibited additional net economic gains of ₹ 43000/ha vis-à-vis higher weed suppression, system crop and water productivity, system economic-efficiency and land–use efficiency over the DSC–based systems. Likewise, planting geometry/planting density of 60 × 45 cm (37037 plants/ha) exhibited significantly higher system productivity (SCEY) (6.58 t/ha), system net returns (₹ 178450/ha), system water-productivity and system economic-efficiency over other two planting geometries viz. 75 × 45 cm and 90 × 60 cm. In nutshell, system-intensification through transplanted *Bt*-cotton based cropping systems (TPC−wheat−mungbean/TPC−onion−fodder cowpea + maize) and planting geometry/planting density of 60 × 45 cm (37037 plants/ha) led to higher weed suppression, system productivity, system economic-efficiency, system water-productivity and land–use efficiency in Indo–Gangetic plains region.

Key words: *Bt* cotton, Land–use efficiency, Profitability, System productivity, System intensification, Transplanted cotton, Water productivity, Weed suppression

Cotton–wheat cropping system (CWCS) is the second most important production system after rice–wheat cropping system (RWCS) in South Asia in general and India in particular with respective acreages of 4.5 and 2.6 M ha, thus, the CWCS contributes significantly to the food security in this region (Choudhary *et al.* 2015, Rajpoot *et al.* 2016a, 2018). Being a cash and grain cropping system, it is highly remunerative with assured returns. However, the sustainability of the direct-seeded cotton–wheat system in the Indo-Gangetic plain region (IGPR) is at risk due to exhaustive nature of this cropping system, inadequate crop stand of cotton due to erratic rainfall and delayed wheat sowing (Choudhary *et al*. 2015, Rajpoot *et al.* 2016a, 2018). Conventional crop establishment methods and crop management practices further result in low CWCS productivity and profitability in the region (Rajpoot *et al.* 2016a, 2018). Cotton is one of the most important commercial crops in India having world's largest acreage of 11.99 M ha with average yield of 512 kg/ha (Choudhary *et al*. 2015, Rajpoot *et al.* 2016a); which is far below the world averages (677 kg/ha) (Choudhary *et al.* 2015, Rajpoot *et al*. 2016a, 2018). Presently, major area under cotton cultivation in northern zone of India comprises hybrids (both Bt and non-Bt). The cultivation of Bt–cotton hybrids has

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evoked a considerable enthusiasm among farmers and farm scientists to boost the cotton productivity at reduced cost of production besides least environmental pollution because of lower pesticide loads (Blaise *et al.* 2014, Choudhary *et al*. 2018). Generally, the second fortnight of May is the optimum cotton sowing time for direct-seeded cotton (DSC) in northern cotton zone of India which requires frequent irrigations and weeding operations owing to high temperature, slow initial crop growth and wider spacing due to poor crop-stand which promotes weed infestation (Rajpoot *et al.* 2016a, Paul *et al*. 2016). These frequent irrigations and weeding operations alleviate the cost of cultivation in May sown crop (Rajpoot *et al.* 2016a, 2018).

On the other hand, declining ground water table, limited surface water resources and inadequate power supply further aggravate the production and resource vulnerabilities in this crop, thus, it becomes inevitable to maintain optimum plant stand under such circumstances (Rana *et al.* 2014a, Choudhary *et al.* 2015, Rajpoot *et al.* 2016a). The DSC method of Bt-cotton is also costlier due to high seed rate and high price of Bt-cotton seed (Rana *et al.* 2014a, Rajpoot *et al.* 2016a, 2018). Optimum planting geometry is a very important non-monetary input to ensure efficient use of natural resources and other inputs, and thus, to get higher productivity we need to optimize the appropriate planting geometry/planting density. Most of the earlier studies have only been focused on sole studies on certain planting patterns or cotton based cropping systems; and only a few have studied the joint effects of different planting patterns in combination with cotton based cropping systems (Du *et al*. 2016). Cotton transplanting has emerged as a recent resource conservation technology which ensures optimum plant stand under adverse conditions with saving of seed, water, nutrients with less weed infestation as compared to direct-seeded cotton besides providing ample scope for crop diversification and intensification (Rana *et al.* 2014a, Rajpoot *et al*. 2016a, 2018).

Keeping in view above facts, the raising of Bt-cotton seedlings in May–June under controlled conditions and their transplanting on the onset of monsoons may prove as a boon to ensure optimum plant stand with reduced cost of cultivation by saving costlier Bt-cotton seed and irrigation water as well (Rajpoot *et al*. 2016a). The transplanted cotton also offers ample opportunities to adjust the 3rd crop in the existing and exhaustive direct-seeded cotton–wheat cropping system like summer legumes, *viz*. summer mungbean, vegetable cowpea and fodder cowpea in the summer window period of April to June (Rajpoot *et al*. 2018); which may further increase the system productivity and profitability besides improving the soil health on sustainable basis. There is much scope to increase the productivity, profitability and resource-use-efficiency of Bt cotton based cropping systems by agronomic manipulations such as method of crop establishment, planting geometry and system intensification. Thus, extensive studies on transplanted *Bt* cotton in cropping system mode inducting legumes/high value crops in combination with appropriate planting geometries/planting densities is the need of the hour. Therefore, current field experimentation was planned to assess the comparative performance of two cotton establishment methods [transplanted cotton (TPC) and direct-seeded cotton (DSC)] with three planting geometries/plant densities [(90 × 60 cm (18518 plants/ha); 75 × 45 cm (29629 plants/ha) and 60 × 45 cm (37037 plants/ha)] under four cropping systems, viz. DSC−wheat; TPC−wheat−mungbean; DSC−onion; and TPC−onion−fodder cowpea + maize cropping system in semi-arid Indo–Gangetic plains region.

MATERIALS AND METHODS

A field experiment was conducted during rainy (*kharif*), winter (*rabi*) and summer season of 2014–15 and 2015–16 at Experimental Farm of ICAR–Indian Agricultural Research Institute, New Delhi, India [28°58' N Latitude; 77°10' E Longitude; 228.6 m Altitude]. The experiment was laid-out in a split-plot-design with four replications comprising two cotton establishment methods (CEMs) [transplanted cotton (TPC) and direct-seeded cotton (DSC)] and three planting geometries/plant densities [(90 × 60 cm (18518 plants/ha); 75 × 45 cm (29629 plants/ha) and 60 × 45 cm (37037 plants/ha)] and four cropping systems *viz*. direct-seeded cotton (DSC)−wheat; transplanted cotton (TPC)−wheat−mungbean; DSC−onion; and TPC−onion−fodder cowpea + maize cropping system under above two CEMs. In the *rabi* and summer seasons, each sub-plot was further divided into two sub-sub plots to adjust wheat, onion and summer mungbean and fodder cowpea + maize, respectively in the above described crop sequences (Table 1).

Supplementary information regarding crops/crop varieties, seed rate, dates of sowing, fertilizer rate and dates of harvesting of all the crops imbedded in system mode are given in Table 1.The climate of above Farm is semi–arid with dry hot summers and cold winters with average annual rainfall of 650 mm, 80% of which is received through South–West Monsoons during July to September, and the rest is received during the Western Disturbances from December to February (Pooniya *et al*. 2017). The mean annual evaporation is 850 mm. The hottest months are May–June with mean daily maximum temperature varying from 40 to 46°C, whereas December–January are the coldest months with mean daily minimum temperature ranging from 5 to 8°C. The mean wind velocity varies between 3.5 km/hr during October and 4.3 km per hour during April. Daily mean values of the meteorological parameters during the year 2014–15 and 2015–16 covering *kharif*, *rabi* and summer crop seasons are recorded at the 'IARI Meteorological Observatory' adjoining to the experimental site. The soil of the experimental field belongs to the major group of Indo–Gangetic alluvium (Typic Ustochrept). The soil of experimental site was sandy–loam (Inceptisol; Mahauli series) with 0.44% soil organic carbon (SOC), soil bulk density 1.53 Mg/m, field capacity 17.5% (w/w), and permanent wilting point (4.3%). The available N, P and K in the soil were 170, 14 and 260 kg/ha, respectively.

For nursery raising of *Bt* cotton, the poly-glasses with

Table 1 Details of agronomic practices followed for different crops in current field experimentation conducted during 2014–15 and 2015–16

Crops under different cropping systems	Cultivars	Seed rate (kg/ha)	Plant spacing (cm)	Date of sowing/ transplanting	Date of harvesting	Fertilizer application rate (NPK kg/ha)
Bt cotton	Bioseed−6588	1-2	As per treatments	1st week of June/1st week of July	Last week of November	150: 60: 40
Wheat (*Triticum aestivum* L.)	HD–3059	125	20	1st week of December	2nd week of April	120: 60: 40
Onion (*Allium cepa* L.)	Pusa Riddhi	10	20	Last week of December	2nd week of May	120: 60: 40
Mungbean (*Vigna radiata* (L). Wilczek)	SML–668	25	30	3rd week of April	3rd week of June	12.5: 40: 0
Cowpea as fodder crop (*Vigna unguiculata* (L). Walp.)	UPC−625	25	30	2nd week of May	1st week of July	25: 40: 0

dimensions of 15 cm height and 10 cm diameter were filled with soil and farm yard manure (FYM) in the ratio of 3: 1. The FYM contained 0.55, 0.28, and 0.51% N, P_2O_5 and K_2O, respectively on oven dry weight basis. One *Bt*-cotton seed was sown in each poly-glass on 1st week of June during 2014 and 2015 and were watered on alternate days till transplanting of one month old seedling during 1st week of July during 2014 and 2015 in similar land configuration and spacing as followed in case of direct-sowing method. Seedlings were transplanted at the centre of the field ridges by making a pit with the help of *khurpa* of desired dimension to place the seedlings then covering and pressing using soil for their easy and faster establishment (Rajpoot *et al.* 2016a, 2018). Direct sowing of *Bt* cotton was done on the same date (1st week of June, 2014 and 2015) as that followed for nursery raising for transplanted cotton (TPC) so as to ideally work-out the real-time productivity and system productivity as well as resource-use efficiency indices in the current study. In direct-seeded cotton (DSC), 2-seeds of *Bt* cotton hybrid *Bioseed* 6588 were dibbled per hill in the centre of broad-beds made using tractor mounted ridge-maker keeping in view the inter-row spacing and intra-row spacing under sub-plot planting geometry/planting density treatments The *Bt* cotton was fertilized with 150: 60: 40 kg N, P_2O_5 and K_2O/ha (Table 1). The N as urea was applied in 2 equal splits i.e. first at sowing/transplanting and remaining half-N at appearance of first flower in *Bt* cotton. The P_2O_5 as single super phosphate and K_2O as muriate of potash were applied at transplanting time in TPC and at sowing time in DSC (Table 1). The DSC received 4–5 irrigations each of 60 mm before onset of monsoon besides one pre-sowing irrigation. *Bt* cotton transplanting was done on onset of the South–West Monsoon using rain moisture with no irrigation during both the years. Irrigation to *Bt* cotton was provided to supplement the rainfall; so both TPC and DSC received one or two irrigations in the post-rain period.

The growth parameters like plant height, leaf area index, dry matter accumulation at 120 DAS and sympodial branches per plant at maturity, were recorded using standard procedures (Rana *et al.* 2014b). The seed cotton was harvested in 4–pickings from 2nd fortnight of October onwards to last week of November during both years and finally the *Bt* cotton sticks were harvested after 4th picking. Net plot of each treatment/crop was harvested at appropriate stage, weighed for economic/biological yield and converted into per ha basis using standard procedures (Rana *et al.* 2014b). Economics of crop cultivation was calculated using prevailing market prices of the inputs and outputs during the respective crop seasons. Net returns were then calculated after subtracting the cost of cultivation from respective gross returns (Rana *et al.* 2014b).

Total number of weeds present in one m^2 area selected at random in each plot, were recorded at 60 and 90 days after sowing (DAS) or transplanting (DAT) under both the CEMs (Table 3). All the weeds present in one m^2 were selected at random and pulled-out at 60 and 90 DAS and then counted. These weeds were air-dried and then oven-dried at 70°C till a constant dry weight was obtained.

System productivity in terms of seed-cotton-equivalent-yield (SCEY) was calculated as: SCEY = Seed cotton yield + [(yield of succeeding wheat crop × price of wheat)/price of seed cotton]. System production–efficiency was expressed as the ratio of system productivity in term of SCEY in kg/ha to total duration of the particular cropping system in days (Kumar *et al*. 2015). Likewise, system economic–efficiency was expressed as the ratio of net returns from a particular cropping system in ₹/ha to the total duration of that system in days (Kumar *et al*. 2015). System water–productivity was worked out using standard procedures (Choudhary *et al.* 2006, Choudhary and Suri 2018a,). The land use efficiency was calculated using formula suggested by Rana *et al.* (2014b). For estimation of above resource-use efficiency (RUE) indices, the mean values of two cropping systems each in TPC–based and DSC–based systems was taken into account (Table 4).

The data were statistically analyzed using *F*–test as per the standard procedure suggested by Rana *et al.* (2014b). Critical difference (CD) values at P=0.05 were used to determine the significant of difference between treatment means.

Table 2 Effect of cotton establishment methods and planting geometry/density on growth and productivity of *Bt*-cotton

Treatment	Plant height (cm) at 120 DAS		LAI at 120 DAS		Dry matter accumulation at 120 DAS (g)		Sympodial branches/ plant at maturity		Seed yield (t/ha)		Lint yield (t/ha)		Harvest index (%)	
	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015
Cotton establishment methods														
Transplanted cotton (TPC)	98.7	105.2	3.8	3.9	335.1	336.3	16.5	17.2	1.55	1.78	0.81	0.95	29.3	28.2
Direct-seeded cotton (DSC)	111.1	115.8	3.9	3.9	349.9	353.0	17.3	18.0	1.47	1.57	0.74	0.79	26.3	26.6
SEm±	0.41	0.25	0.02	0.01	1.20	0.91	0.27	0.38	0.03	0.07	0.02	0.02	0.40	0.77
CD (P=0.05)	1.30	0.79	NS	NS	3.80	2.86	NS	NS	NS	0.21	0.06	0.07	1.25	NS
Planting geometry/plant density														
90×60 cm (18518 plants /ha)	101.5	107.2	3.1	3.2	351.0	353.0	18.4	19.0	1.33	1.43	0.71	0.76	27.5	25.3
75×45 cm (29629 plants /ha)	104.2	110.3	4.1	4.1	343.2	344.2	17.3	18.4	1.45	1.61	0.75	0.85	27.4	26.8
60×45 cm (37037 plants /ha)	109.0	114.0	4.4	4.4	333.3	336.8	16.2	17.5	1.76	1.99	0.88	1.01	28.5	30.3
SEm±	0.50	0.31	0.03	0.01	1.48	1.11	0.37	0.47	0.04	0.08	0.03	0.03	0.49	0.94
CD (P=0.05)	1.59	0.97	0.09	0.04	4.65	3.51	1.09	1.47	0.11	0.25	0.08	0.09	NS	2.98

TPC–Transplanted cotton; DSC = Direct-seeded cotton; LAI = Leaf area index; DAS = Days after sowing.

RESULTS AND DISCUSSION

Seasonal weather variations

The agro-meteorological data of the experimental site covering whole experimental period, i.e. *kharif, rabi* and summer seasons of two consecutive years, viz. 2014–15 and 2015–16, recorded at the Meteorological Observatory of the ICAR–Indian Agricultural Research Institute, New Delhi. We know that the weather situations are accredited to have an immense impact on the performance of the field crops (Rana *et al.* 2014b). So, it becomes inevitable to take a glance of the meteorological parameters to frame to a valid conclusion of the results of field experiments. Here, we found that during 2015–16, the rainy season was quite wet with rainfall of 749 mm which was higher than the average rainfall (672 mm). In contrast to this, during the rainy season of 2014–15, the onset of monsoon was late and there was also intermittent drought and rainfall was just 76% of the average normal rainfall. In the winter season trend was reverse that of rainy season and more rainfall was recorded during 2014–15 (264 mm) than 2015–16 (19.8 mm).

Growth, yield attributes and seed cotton yield

Plant height and dry matter accumulation (DMA)/ plant recorded at 120 DAS/DAT recorded under DSC-cotton were significantly higher than TPC-cotton. The sympodial branches per plant and leaf area index (LAI) were statistically similar in DSC and TPC. Data in Table 2 revealed a significant decline in plant height, LAI and DMA/plant under TPC as compared to DSC. This decrease in growth attributes under TPC may be ascribed to the transplanting shock to the crop, resulting in slower root development and plant growth compared to DSC (Rajpoot *et al*. 2016a, 2018). Moreover, due to less plant stand under DSC compared to TPC, the crop got more space below and above the ground for its growth and development which ultimately contributed greatly towards higher values of growth attributes in TPC-cotton (Dong *et al.* 2005, Rajpoot *et al*. 2016a, 2018). Despite higher values of growth and yield attributes in DSC, the lint yield per ha was about 15% higher under TPC which may be attributed to 14–15% higher plant stand under TPC than the DSC (Table 2). Similarly, the seed yield was higher by ~9.54% under transplanted-cotton (TPC) due to better plant stand under TPC. Higher harvest index (%) of TPC may be attributed to more reproductive growth and uniform maturity of the Bt-cotton bolls under TPC as compared to DSC, where the vegetative growth was more robust resulting in quite delayed maturity (Choudhary *et al.* 2010, Rana *et al*. 2014a). The plant stand of DSC-cotton was not uniform owing to repeated gap fillings resulting in poor crop stand under harsh weather in early crop establishment stage in DSC.

Planting geometry/plant density significantly influenced the plant growth parameters, seed and lint yields during both the years under study (Table 2). Among different planting geometries/plant densities, the spacing of 60 × 45 cm (37037

Table 3 Effect of cotton establishment methods and planting geometry/density on weed population and weed dry weight in *Bt*-cotton

Treatment	Weed population (Number/m^2)				Weed dry weight (g/m^2)			
	60 DAS/DAT		90 DAS/DAT		60 DAS/DAT		90 DAS/DAT	
	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
Cotton establishment methods								
Transplanted cotton (TPC)	12.2	14.4	16.4	18.3	20.6	21.8	24.4	25.9
Direct-seeded cotton (DSC)	33.9	37.3	19.4	22.0	62.9	64.1	27.4	28.7
SEm ±	0.65	0.99	1.22	1.18	0.55	0.49	0.37	0.48
CD (P = 0.05)	2.06	3.13	NS	NS	1.72	1.53	1.16	1.51
Planting geometry/plant density								
90×60 cm (18518 plants /ha)	29.0	31.5	21.0	23.8	43.8	44.8	28.0	29.3
75×45 cm (29629 plants /ha)	22.5	26.2	17.7	19.3	41.7	43.2	26.0	27.2
60×45 cm (37037 plants /ha)	17.7	20.0	15.2	17.3	39.7	40.8	23.8	25.3
SEm ±	0.80	1.22	1.49	1.45	0.67	0.59	0.45	0.59
CD (P = 0.05)	2.53	3.84	4.70	4.57	2.11	1.87	1.42	1.84

TPC–Transplanted cotton; DSC = Direct-seeded cotton; LAI = Leaf area index; DAS = Days after sowing; DAT = Days after transplanting.

plants/ ha) significantly influenced the growth parameters as compared to 75 × 45 cm (29629 plants/ha) and 90 × 60 cm spacing (18518 plants/ha). Since, closer crop geometry leads to taller plants owing to less available horizontal space and more plant thrust for vertical space which resulted in more taller plants with more accommodation of plants per unit area (Salakinkop 2011), all of which resulted in higher plant height and LAI but with lower DMA over the wider crop geometry where horizontal spread was more as evident from sympodial branches count per plant in Table 2. On an average, planting geometries of 75 × 45 cm and 60 × 45 cm exhibited a respective enhancement of about 10.8 and 35.5% in cotton seed yield, and 9.5 and 28.7% in lint yield over planting geometry of 90 × 60 cm (Table 2). Increase in seed cotton yield and stalk yield in close density (60 × 45 cm) may be ascribed to accommodation of higher number of plants per unit area. The advantage of closer planting was more under TPC-cotton owing to its compact growth habit avoiding inter- and intra-row competition besides suppressing weeds resulting in more cotton yield (Rajpoot *et al*. 2016a,b, 2018, Paul *et al*. 2016). Thus, planting at an optimum planting geometry for efficient interception of radiant energy at the crop surface is an important agronomic consideration to improve the productivity of any crop under given set of resource-base and environmental conditions as well (Choudhary *et al.* 2006, Rana *et al.* 2014a).

Weed dynamics

Weed population and weed dry weight (WDW) at 60 DAS/DAT were significantly influenced by the CEMs being more under DSC-cotton probably because of poor crop stand under harsh initial weather conditions vis-à-vis more weed infestation over TPC-cotton (Rajpoot *et al*. 2016a). In contrast to Bt cotton nursery for TPC-cotton, the soil surface temperature under DSC-cotton remains very high in semi-arid IGPR (sometimes >50°C) as compared to ambient atmosphere temperature which attributes to poor germination of DSC-cotton with more mortality of germinated seeds (Rana *et al.* 2014a, Rajpoot *et al.* 2016a). Due to higher mortality of the germinated seeds even after 20 to 30 DAS, it was not generally feasible to maintain optimum plant stand under DSC-cotton (even after repeated gap filling). On the other hand, in TPC-cotton the mortality percentage after transplanting was drastically low resulting in higher plant stand as compared to DSC-cotton, thus, resulting in meager chances for weed proliferation due to less available space and land (Rana *et al.* 2014a, Rajpoot *et al.* 2016a). In case of planting geometry, no significant effects were observed on weed population and WDW at both the stages, viz. 60 and 90 DAS/DAT. In planting geometry of 60 × 45cm, the lower values of WDW were obtained due to smothering effect owing to less available space for weed growth and proliferation (Rajpoot *et al*. 2016a, Paul *et al*. 2016).

System productivity

Four cropping systems were followed under two CEMs (TPC and DSC), viz. TPC–wheat–mungbean (TPC–W–M_b), TPC–onion–fodder cowpea + maize (TPC–O–Fc+M), DSC–wheat (DSC–W), and DSC–onion (DSC–O) cropping systems (Table 4). The average system productivity of these TPC–based (TPC–W–M_b/TPC–O–Fc+M) and DSC–based cropping systems (DSC–W/DSC–O) in terms of seed-cotton-equivalent-yield (SCEY) indicated that significantly highest system productivity (SCEY) was registered in TPC–based cropping systems during 2014–15 (6.75 t/ha) and 2015–16 (6.96 t/ha), respectively (Table 4). This increase in system productivity may be attributed to crop diversification and intensification with the vegetable crops and legumes which proved to be more productive and remunerative (Choudhary *et al.* 2013, Singh *et al.* 2013, Paul *et al.* 2016).

Table 4 Effect of cotton-establishment-method based system-intensification and planting geometry/density on system crop and water productivity, system profitability, system production–efficiency, system economic–efficiency and land–use efficiency

Treatment	System productivity in terms of SCEY (t/ha)		System net returns ($\times 10^3$ ₹/ha)		System net B: C ratio		Total water use on system basis (m^3)		System water productivity (kg SCEY/m^3 water use)		System production efficiency (kg/ha/day)		System economic efficiency (₹/day)		Land use efficiency (%)	
	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
Cotton establishment method based cropping systems																
TPC–W–M_b/TPC–O–F_c+M	6.75	6.96	176.9	191.45	1.55	1.65	7900	7600	0.83	0.90	22.50	23.20	176.9	191.5	176.9	191.5
DSC–W/DSC–O	5.42	5.45	137.55	144.75	1.30	1.50	7200	7500	0.73	0.72	20.08	20.19	137.6	144.8	137.6	144.8
SEm ±	0.08	0.09							0.01	0.01						
CD (P = 0.05)	0.23	0.27							0.03	0.04						
Planting geometry/plant density																
90×60 cm (18518 plants/ha)	5.84	5.78	149.2	152.7	1.4	1.5	7550	7550	0.75	0.75	20.49	20.28	408.8	418.4	78.1	79.0
75×45 cm (29629 plants /ha)	5.98	6.13	152.7	164.5	1.4	1.5	7550	7550	0.77	0.79	20.98	21.51	418.4	450.7	78.1	79.0
60×45 cm (37037 plants /ha)	6.44	6.71	169.8	187.1	1.5	1.7	7550	7550	0.83	0.87	22.60	23.54	465.2	512.6	78.1	79.0
SEm ±	0.12	0.05							0.02	0.01						
CD (P = 0.05)	0.46	0.20							0.06	0.03						

TPC–W–M_b = Transplanted-cotton (TPC)–wheat (W)–mungbean (Mb) cropping system; TPC–O–Fc+M = TPC–onion (O)–fodder cowpea + maize (F_c+M) cropping system; DSC–W = Direct-seeded-cotton (DSC)–wheat (W) cropping system; DSC–O = DSC–onion (O) cropping system; SCEY= Seed-cotton equivalent yield.

On an average, legume-intensification led to about 26–27% increase in system productivity in TPC–based cropping systems over DSC–based cropping systems (Pooniya *et al.* 2018, Rajpoot *et al.* 2018). Likewise, system productivity with 60 × 45 cm spacing of Bt cotton was 8.5 to 13% higher than the other two geometries owing to higher SCEY of respective component crops (Table 4).

System profitability

The average system net returns were lower in DSC–based cropping systems than the TPC–based cropping systems due to crop intensification with high value crops like onion and legumes, which led to higher system net returns and benefit: cost ratio in current study (Table 4). This could be attributed to variation in *Bt* cotton yield under TPC and DSC as well as the additional yield of component/additional crops under TPC–based cropping systems, varying cost of cultivation and more remunerative price of high value crops/ pulses (Choudhary *et al*. 2013, Rana *et al*. 2014a, Rajpoot *et al.* 2016a, 2018). On an average, plant density of 60 × 45 cm imbedded cropping systems exhibited highest system net returns (₹ 178450/ha) as compared to two geometries, i.e. 75 × 45 cm (₹ 158600) and 90 × 60 cm (₹ 150950) (Table 4). This might be due to more efficient use of resources such as seed, irrigation water, higher plant population as well as more solar radiation interception which collectively led to higher system gross and net returns, and benefit cost ratio in close density of planting (Ehsan *et al.* 2017a).

System water-productivity

Water productivity on system basis was significantly higher in TPC–based cropping systems over DSC–based cropping systems due to less water requirement and high system productivity (Table 4). The May-June sown DSC–cotton have poor germination and high rate of seedling mortality due to very high surface soil temperature ranging from 48 to 52°C, resulting in poor plant stand. The poor crop stand establishment may be there due to poor soil conditions in semi-arid IGPR generally dominated by sandy-loam texture with low soil organic matter resulting in low water holding capacity (Rana *et al.* 2014a). The high soil temperature coupled with high evapo-transpiration also leads to accumulation of salts and crust formation hindering seedling emergence which led to more seedling mortality in one hand and more irrigation water use on the other (Rana *et al.* 2014a). Thus, the system crop and water productivity was quite low under DSC–cotton based cropping systems as compared to TPC–cotton based cropping systems (Table 4). Frequent irrigations were required to ensure emergence of cotton seedlings and their survival till the onset of South-West Monsoon which led to higher irrigation water-use under DSC-cotton resulting in low water productivity (Rajpoot *et al*. 2016a, Paul *et al*. 2016). The yield variation in component crops and their differential water requirements (Rana *et al.* 2014b), also affected the total system water-use and system water productivity in the current study (Table 4). Among different planting geometries/plant densities, 60 × 45 cm geometry exhibited higher system water productivity (0.83–0.87 kg/m^3) over other two planting geometries (Table 3) owing to higher SCEY of respective crops under this geometry (Table 4).

System production–efficiency, system economic–efficiency and land-use efficiency

The TPC–based cropping systems exhibited higher system production–efficiency (SPE), system economic–efficiency (SEE) and land–use efficiency (LUE) over DSC–based cropping systems during both the years (Table 4). This increase in SPE, SEE and LUE under TPC–based cropping systems might be possible due to additional SCEY of component crops as accommodated as 3^{rd} crop under TPC-based cropping systems as a result of elimination of summer-window period of about 55–65 days owing to cotton-transplanting technology (Rana *et al.* 2014a). Thus, the cultivation of short-duration summer crops (mungbean/ fodder cowpea) as 3^{rd} crop in this summer window period substantially enhanced the SPE, SEE and LUE under TPC–based cropping systems (Table 4). Such improvements in resource-use efficiency (RUE) indices were also reported by Gill and Jat (2007) and Choudhary and Rahi (2018). On an average, respective increase in SPE and SEE under 60×45 cm planting geometry was 13.19 and 8.61%, and 18.2 and 12.5% over 90 × 60 cm and 75 × 45 cm planting geometry of *Bt*-cotton, respectively (Ehsan *et al.* 2017b).

Conclusion

It is concluded that the direct-seeded-cotton (DSC) resulted in higher plant growth though the seed yield and lint yield were higher by ~9.54% and ~15%, respectively under transplanted-cotton (TPC) due to better plant stand under TPC. Likewise, the highest system productivity in terms of seed-cotton-equivalent-yield (SCEY) was registered under TPC–wheat—mungbean/TPC–onion–fodder cowpea + maize cropping systems (6.75, 69.6 t/ha) during 2014–15 and 2015–16, respectively. On an average, the legume-intensification in TPC–based cropping systems exhibited about 25–27% higher system productivity (SCEY) over the DSC–based cropping systems (DSC–wheat/DSC–onion) in current study. The TPC–based cropping systems (mean value of two systems) also exhibited additional net economic gains of about ₹ 43000/ha vis-à-vis higher weed suppression, system productivity, system water-productivity, system economic-efficiency and land–use efficiency over the DSC–based cropping systems (mean value of two systems) during both the years. Likewise, planting geometry of 60 × 45 cm (37037 plants/ha) exhibited significantly higher system productivity, system net returns, system water-productivity and system economic-efficiency compared to other two planting geometries. In nutshell, system-intensification through transplanted *Bt* cotton based cropping systems (TPC−wheat−mungbean/ TPC−onion−fodder cowpea + maize) and planting geometry/planting density of 60 × 45 cm (37037 plants/ha) led to higher weed suppression, system productivity and profitability, system water-productivity, system economic efficiency and land use efficiency in Indo–Gangetic plains.

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