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# Brown manuring optimization in maize: impacts on weeds, crop productivity and profitability

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*Cyperus rotundus*; integrated weed management; maize yield and economics; *Sesbania* co-culture; tank-mix atrazine + pendimethalin

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## Abstract

Field experiments were carried out in order to investigate if brown manuring (BM) using *Sesbania* plants can be used to control weeds in maize, especially *Cyperus rotundus* (Experiment I), and further to optimize the BM technology through appropriate *Sesbania* seed rate (S), 2,4-D application time (T) and dose (D) (Experiment II). Each BM treatment received a pre-emergence application of pendimethalin 1.0 kg a.i./ha. Experiment I showed that the BM practice using 15 kg/ha *Sesbania* seed and 2,4-D 0.50 kg a.i./ha applied at 25 DAS led to better control of weeds, especially *C. rotundus* and higher maize grain yield. Further optimization studies (Experiment II) indicated that among the factors S, T and D, the BM combination S∼25 kg/ha, D∼0.50 kg a.i./ha and T∼25 DAS (i.e. $S_{25}T_{25}D_{0.50}$) resulted in lowest weed density (3.1/m$^2$) and dry weight (3.8 g/m$^2$) and highest weed control index (89.2%) at 60 days after sowing (DAS) which was at par with another BM practice $S_{15}T_{25}D_{0.50}$. However, the later BM combination led to significantly higher maize productivity (5.25 t/ha) and profitability (net returns (NR) $878/ha), which were 103 and 280% higher, respectively, than the weedy check (WC). The *Sesbania* seed rate S∼15 kg/ha gave 7% higher maize grain yield and 12% higher NR than its corresponding level S∼25 kg/ha. Therefore, *Sesbania* BM with 15 kg seeds/ha and 2,4-D at 0.50 kg a.i/ha applied at 25 DAS can be recommended for effective and eco-friendly weed management in maize, which would provide higher maize grain yield and enhance farmers' profitability.

## Introduction

Maize is the third most important food crop in India, after rice and wheat, cultivated in an area of 9.5 million hectares with an annual production of 24.5 million tonnes (Susha *et al.*, 2018). The adaptability of maize to diverse agro-ecologies and seasons along with high yield potential is unmatched to any other crops (Dass *et al.*, 2008; Sharma *et al.*, 2011). Maize can be a potential driver for diversification of the predominant rice–wheat cropping system in the Indo-Gangetic Plains of India (Gupta and Seth, 2007; Ladha *et al.*, 2009; Saad *et al.*, 2016; Das *et al.*, 2018) and contribute to food and nutritional security of the nation. The low yields of maize (∼2.44 t/ha) in India are the outcome of several factors of which weed infestation appears to be the most critical. Wide spacing and slow initial growth rate of maize crop favour the preponderance of weeds, competing with the crop for nutrients, water, sunlight and space. Presence of weeds reduces the photosynthetic efficiency, dry matter production and distribution to economical parts and there by reduces the sink capacity of the crop resulting in poor grain yield (Das and Yaduraju, 2011). Weed interference can cause maize yield losses by 15–75% (Sen *et al.*, 2000), 84.3% (Pandey *et al.*, 2001) and 15–85% (Susha *et al.*, 2014). Brown manuring (BM) is the 'no-till' form of green manuring wherein a selective herbicide is applied to desiccate the legume plants before flowering rather than using cultivation. The existing BM technique adopted for rice involves growing *Sesbania bispinosa* (hereafter referred to as *Sesbania*) with the crop as a co-culture for the initial 25–30 days after sowing (DAS) and thereafter knocked down by a selective herbicide 2,4-D (Maitra and Zaman, 2017). *Sesbania* leaves/residue become brown/yellow in colour upon degradation of chlorophyll and hence referred to as 'brown manure'. The dead *Sesbania* residues are left standing in the field along with the main crop until they decompose *in situ* thereby adding organic manure. Principally, *Sesbania* as a live cover offers interference (at pre-killing period) initially, and later as a dead residue mulch offers stimulation (at post-killing period). The study of Oyeogbe *et al.* (2017) indicates that BM decreases weed interference through smothering effects or allelopathy and reduces herbicide dose and residue in the soil. This will reduce herbicide intake into the environment (Das, 2001; Gupta and Seth, 2007; Singh *et al.*, 2007; Ladha *et al.*, 2009; Sharma *et al.*, 2010*a*; Ramachandran *et al.*, 2012; Das *et al.*, 2014*a*). Besides, *in situ Sesbania* biomass like other residues can conserve soil moisture (Lal, 1997; Sharma *et al.*, 2010*a*, 2010*b*) and reduce irrigation

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water requirement, sequester C and N in the soil (Singh *et al.*, 2005; Sharma *et al.*, 2010*a*, 2010*b*; Verhulst *et al.*, 2011; Bhattacharyya *et al.*, 2013; Das *et al.*, 2013; Bhattacharyya *et al.*, 2015), reduce greenhouse gases emissions and mitigate climate change (Lal, 2004; Oyeogbe *et al.*, 2017) and increase crop yield and farm income (Jalota *et al.*, 2008; Sharma *et al.*, 2010*a*, 2010*b*, 2011). *Sesbania* BM in rice decreased weed density by 37–42% (Singh *et al.*, 2009) and 41–56% (Nawaz *et al.*, 2017). Gangaiah and Babu (2016) reported that BM crop (*Sesbania*) generated up to 1.21 t/ha dry biomass and 3.09 t/ha fresh biomass in 30 days and thereby accumulated 35.7, 3.9 and 17.2 kg/ha nitrogen, phosphorous and potassium, respectively. Moreover, BM reduced the weed biomass production (g/m$^2$) by 40.5%.

An emerging weed problem in arable cropping systems has been the preponderance of perennial weed, *Cyperus rotundus* reported in maize (Susha *et al.*, 2014), soybean (Tuti and Das, 2011; Kumar *et al.*, 2012; Das *et al.*, 2014*b*), tomato (Gilreath and Santos, 2004), etc. Furthermore, the recommended selective herbicides for maize in India like atrazine, pendimethalin, alachlor, 2,4-D, etc., has limited efficacy in controlling the aforesaid weed (Singh *et al.*, 2010; Behera *et al.*, 2018). Therefore, we investigated if *Sesbania* BM could be used to control *C. rotundus* and other weed species due to *Sesbania*'s competitive ability (fast germination and emergence, fast growth resulting in high shading ability, below-ground competition for water and nutrients). The present study aims to develop a BM practice with optimum *Sesbania* seed rate, and time and dose of herbicide (2,4-D) application in maize crop with respect to weed control, crop productivity and economic feasibility. The hypotheses were: an optimized BM practice could control weeds better in maize without undue interference to crop; and this BM combined with a pre-emergence broad-spectrum selective herbicide would lead to better management of diverse weeds and harness higher maize yield and income. The specific objectives of the study were: to compare the overall effects of BM on weed management with that of the recommended herbicide through a preliminary trial (Experiment I); and to optimize the seed rate of *Sesbania*, and time, and dose of 2,4-D for achieving adequate weed management and superior maize yield and profitability (Experiment II).

## Materials and methods

### Experimental sites

The experiments were undertaken under natural weeds infestations in maize during rainy seasons (July to October) in 2011–2014 (~4 years) at the ICAR-Indian Agricultural Research Institute, New Delhi (28°35′N latitude, 77°12′E longitude and at an altitude of 228.6 m above mean sea level). The climate is subtropical, semi-arid with 710 mm annual rainfall. About 80% of the annual rainfall is received during July–September when maize is grown. The differences between maximum and minimum temperatures and rainfall on a daily basis in maize growing period during 2012–2014 are presented in Figs 1(*a*) and (*b*). The experimental field soil (Inceptisol; Typic Haplustept) was well drained and sandy loam (at 0–0.15 m depth). The initial status of soil (before starting of these experiments): slightly alkaline (pH 7.8); organic C 0.51% (Walkley and Black, 1934); electrical conductivity 0.64 dS/m; both available P and K were medium with 23.3 kg $P_2O_5$/ha (Olsen *et al.*, 1954) and 250.5 kg $K_2O$/ha (Jackson, 1973); and available N was low with 272.6 kg N/ha (Subbiah and Asija, 1956). The status of N, P and K is according to the nutrients rating chart available for Indian soils.

### Experiments, treatments and herbicides

*Experiment I*: This was a preliminary trial with six treatments (Table 1) and four replications, laid out in a randomized complete block design. The objective was to compare/evaluate the effects of two BM modules (BM I and II) with the recommended weed management practices in maize (ICAR-Indian Agricultural Research Institute, New Delhi, India), *viz.*, atrazine + 1 hand weeding and atrazine + pendimethalin, towards controlling weeds including *C. rotundus* in maize-growing regions of India.

*Experiment II*: This study involved 11 treatments (Table 1) comparing eight BM combinations ($T_1$ to $T_8$) with three controls ($T_9$, $T_{10}$ and $T_{11}$). The BM treatments included a three-way factorial combination of *Sesbania* seed rates (15 and 25 kg/ha), 2,4-D dose (0.25 and 0.50 kg a.i./ha) and application time (25 and 35 DAS). The controls comprised recommended tank-mixture application of atrazine 0.75 kg a.i./ha + pendimethalin 0.75 kg a.i./ha (atrazine + pendimethalin; control 1), weedy control (WC; control 2) and weed-free control (WFC; control 3). Compared to the BM treatments adopted in Experiment I, one higher *Sesbania* seed rate at 25 kg/ha and one extended date for the killing of *Sesbania* at 35 DAS were adopted in this study in order to maximize the BM effects on weeds. *Sesbania* plants, being very succulent and highly susceptible to 2,4-D, another treatment with 50% lower dose of 2,4-D at 0.25 kg a.i./ha was adopted to economize BM. The gross plot area was 5.0 m × 4.9 m (~7 rows; 5 m long). The net plot areas (the area actually harvested for yields) were 3.5 m × 4.0 m (5 rows; 4 m long). For BM, *Sesbania* seeds at 10, 15 or 25 kg/ha (as applicable) were sown uniformly by broadcasting in the respective treatments before the sowing of maize, and wrecking (i.e. slight stirring of surface 0–0.05 m soil by a hoe) was done to cover *Sesbania* seeds with the soil.

Pendimethalin, which is selective to both maize and *Sesbania*, was applied at 1.0 kg a.i./ha as pre-emergence at 2 DAS in all BM treatments to control initial flushes of weeds. 2,4-D at 0.25 and 0.50 kg a.i./ha was applied at 25 and 35 DAS, which resulted in gradual drying up of *Sesbania* plants that served as dry mulch. Weeds were allowed to grow with crops throughout the crop-growing period in WC, whereas weeds were removed through four manual weeding, done at 15, 30, 50 and 70 DAS for making plots weed-free throughout the cropping period in WFC. Atrazine and pendimethalin at required quantities were mixed in the spray-tank just before application at 2 DAS. All herbicides were applied with 400 litres/ha water using a knapsack sprayer, fitted with a flat fan nozzle (Sukun Agencies India, Mumbai, Maharashtra, India).

### Crop sowing and agronomic practices

Maize (cv. HQPM 1) was sown on plain/flat land with 0.7 m (row–row) × 0.3 m (plant–plant) spacing at 0.03–0.04 m depths using 20 kg seed/ha. The dates of sowing were 7 July 2011, 10 July 2012, 2 July 2013 and 5 July 2014 and the emergence of maize was recorded on 12 July 2011, 15 July 2012, 6 July 2013 and 10 July 2014. To facilitate sowing, a manually-operated hand plough was used to open small furrows along the rows. Two maize seeds were dibbled at 0.30 m distance (forming a hill) to maintain plant to plant spacing along the rows. Maize seedlings were thinned to one plant per hill upon emergence. Maize continued to grow throughout the rainy season (July–October) and was harvested on 26 October 2011, 27 October 2012, 22 October 2013 and 25 October 2014. Depending on the rainfall received and resultant soil surface cracking observed, four irrigations were applied to maize in 2011, 2012 and 2014,

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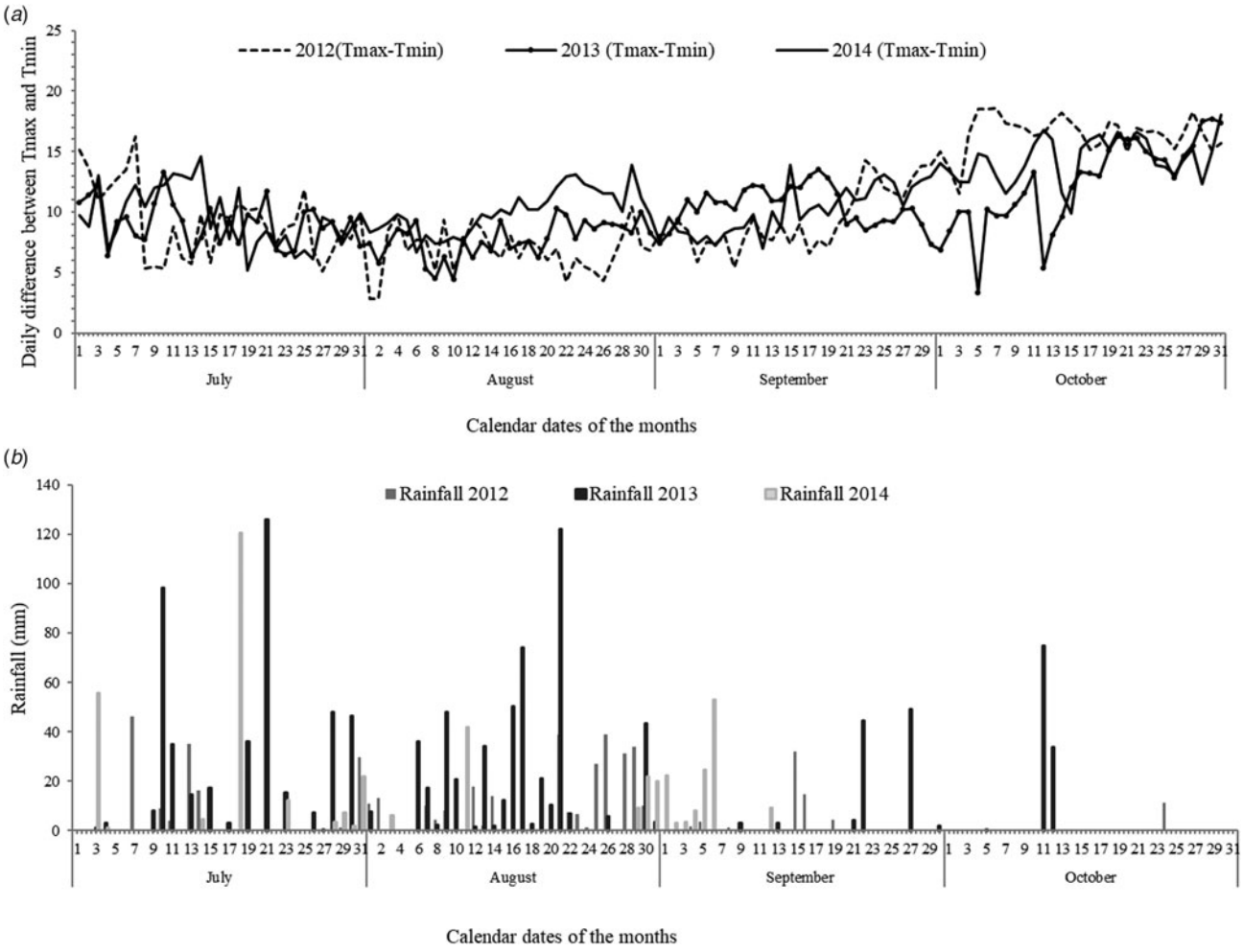



**Fig. 1.** Temperature (°C) and rainfall (mm) during 2012, 2013 and 2014 in maize: (*a*) daily differences between maximum (Tmax) and minimum (Tmin) temperatures; (*b*) daily rainfall (mm).

whereas five irrigations were given in 2013 in all treatments. A recommended dose of 120 kg N, 60 kg $P_2O_5$ and 40 kg $K_2O$ per ha in the form of urea, single superphosphate and muriate of potash, respectively, was applied to maize. Half dose of N and full dose of P and K were applied at sowing, and the remaining N was top-dressed in equal amounts at 30 and 60 DAS. No diseases appeared in maize. Stem borer and shoot fly infestations were observed in maize, and carbofuran (3G) 25 kg/ha was applied along maize crop rows to control these insects.

### *Analyses for weed control effects*

Weeds were collected by pulling out from an area of 0.90 m length (along the rows; 3 maize plants) and 0.70 m width (across the rows; 1 row width) at 60 DAS. This area was randomly chosen involving one central row in each plot. Weed species were identified, counted and kept for sun-drying for 2 days, and, then, were put in an oven at 70 ± 5 °C for 48 h for recording dry weights. Weed control efficiency (WCE), which reflects per cent reduction in weed density by a treatment, was determined using Eqn (1) (Nath *et al.*, 2016).

$$\mathrm{WCE}(\%) = (\mathrm{WP_c} - \mathrm{WP_t})/\mathrm{WP_c} \times 100 \quad (1)$$

where $\mathrm{WP_c}$ and $\mathrm{WP_t}$ are the weed density (no./$m^2$) in WC and treatment plots, respectively.

Weed control index (WCI), which reflects per cent reduction in weed dry weight by a treatment, was determined using Eqn (2) (Nath *et al.*, 2016).

$$\mathrm{WCI}(\%) = (\mathrm{WD_c} - \mathrm{WD_t})/\mathrm{WD_c} \times 100 \quad (2)$$

where $\mathrm{WD_c}$ and $\mathrm{WD_t}$ are the weed dry weights (g/$m^2$) in WC and treated plots, respectively.

Weed index (WI), which reflects per cent yield loss due to weeds in a treatment, was calculated using Eqn (3) (Asres and Das, 2011).

$$\mathrm{WI}(\%) = (Y_{\mathrm{wf}} - Y_{\mathrm{t}})/Y_{\mathrm{wf}} \times 100 \quad (3)$$

where $Y_{\mathrm{wf}}$ and $Y_{\mathrm{t}}$ are the maize yields in WFC and treatments, respectively.

### *Maize and* Sesbania *emergence, maize leaf area index and yield*

The days of emergence of maize, *Sesbania* and weeds were recorded from all plots including BM plots through daily

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**Table 1.** Details of treatments adopted in the Experiments I and II

| Experiment I (2011) | |
|---|---|
| Treatment descriptions | Treatments short forms |
| Atrazine 0.75 kg a.i./ha + pendimethalin 0.75 kg a.i./ha as tank-mix pre-emergence at 2 days after sowing (DAS) | Atrazine + pendimethalin |
| Atrazine 1.0 kg a.i./ha at pre-emergence 2 DAS + hand weeding at 30 DAS | Atrazine + HW |
| Brown manuring (BM) with *Sesbania aculeata* L.at10 kg/ha(1.0 g/m$^2$), 2,4-D 0.50 kg a.i./ha applied at 25 DAS. {A pre-emergence application of pendimethalin 1 kg a.i./ha was undertaken. *Sesbania* seeds were broadcast at the time of sowing of maize. Killing and drying of *Sesbania* plants served as live and dead mulch for initial 35–40 DAS} | BM I |
| Brown manuring with *Sesbania aculeata* L.at 15 kg/ha (1.5 g/m$^2$), 2,4-D 0.50 kg a.i./ha applied at 25 DAS (Practices same as BM I) | BM II |
| Weedy control (No weed control measures were adopted throughout the crop growing period) | WC |
| Weed-free control (Weeds were removed manually throughout the crop growing period) | WFC |
| Experiment II (2012–2014) | |
| Treatment description [Brown manuring (BM)/weed control options] | |
| 15 kg/ha (1.5 g/m$^2$) *Sesbania* seed + 2,4-D applied at 25 DAS with 0.25 kg a.i./ha[a] | $T_1$ : $S_{15}$ $T_{25}$ $D_{0.25}$ |
| 15 kg/ha *Sesbania* seed + 2,4-D applied at 25 DAS with 0.50 kg a.i./ha | $T_2$: $S_{15}$ $T_{25}$ $D_{0.50}$ |
| 15 kg/ha *Sesbania* seed + 2,4-D applied at 35 DAS with 0.25 kg a.i./ha | $T_3$: $S_{15}$ $T_{35}$ $D_{0.25}$ |
| 15 kg/ha *Sesbania* seed + 2,4-D applied at 35 DAS with 0.50 kg a.i./ha | $T_4$: $S_{15}$ $T_{35}$ $D_{0.50}$ |
| 25 kg/ha (2.5 g/m$^2$) *Sesbania* seed + 2,4-D applied at 25 DAS with 0.25 kg a.i./ha | $T_5$: $S_{25}$ $T_{25}$ $D_{0.25}$ |
| 25 kg/ha *Sesbania* seed + 2,4-D applied at 25 DAS with 0.50 kg a.i./ha | $T_6$: $S_{25}$ $T_{25}$ $D_{0.50}$ |
| 25 kg/ha *Sesbania* seed + 2,4-D applied at 35 DAS with 0.25 kg a.i./ha | $T_7$: $S_{25}$ $T_{35}$ $D_{0.25}$ |
| 25 kg/ha *Sesbania* seed + 2,4-D applied at 35 DAS with 0.50 kg a.i./ha | $T_8$: $S_{25}$ $T_{35}$ $D_{0.50}$ |
| Atrazine 0.75 kg a.i./ha + pendimethalin 0.75 kg a.i./ha as tank-mix pre-emergence applied at 2 DAS (Control 1) | $T_9$: Atrazine + pendimethalin ($C_1$) |
| Weedy control (No weed control measures were undertaken throughout the cropping cycle) (Control 2) | $T_{10}$: WC ($C_2$) |
| Weed-free control (Weeds were removed manually throughout the cropping cycle) (Control 3) | $T_{11}$: WFC ($C_3$) |

[a]In all brown manuring treatments, pendimethalin, which is selective to both maize and *Sesbania* was applied pre-emergence with 1.0 kg/ha at 2 DAS to kill initial flushes of weeds.

observation from 2 DAS onwards. The emergence was recorded when two cotyledonary leaves of *Sesbania* and broad-leaved weeds (BLWs), and the cotyledonary leaf of maize and grassy weeds of approximately 75% of plants emerged from the soil. Maize leaf area, which reflects the overall photosynthetic activity of maize plants across treatments, was recorded at 60 DAS. Three maize plants, having a land area of 0.90 m × 0.70 m, were collected from the place where weeds were sampled (mentioned above) at 60 DAS. All maize leaves were separated from plants and their area was measured using a leaf area meter (LI-COR 3100, LI-COR, Lincoln, NE, USA) and leaf area index (LAI) was determined using Eqn (4).

$$\text{LAI} = (\text{Plants leaf area/land area occupied by those plants}) \quad (4)$$

At maturity, maize cobs were harvested from the net plot areas across the treatments and cobs were dehusked manually. Grains were separated from the cobs by using a Sheller machine (Bharat Industries, Karnal, Haryana, India), weighed and grain yield was reported at 15% moisture (Oyeogbe *et al.*, 2017).

### *Maize production economics*

The cost for all treatments included common costs of agronomic inputs/operations (namely, tillage, seed, sowing, fertilizers, irrigation, plant protection, harvesting, threshing, etc.) required for maize cultivation and costs of inputs/operations such as the costs of *Sesbania* seed, 2,4-D and its application, hand weeding, etc., required extra for particular treatment. All these costs were determined as per the prevailing market prices of respective inputs/operations. Gross returns (GR) was determined using Eqn (5). The net returns (NR) and net benefit:cost (NB:C) were worked out following Eqns (6) and (7), respectively. The NB:C is the NR (in $) that could accrue from investing $1.0 in the cost of production. All costs/values in Indian Rupees (INR/ha) were converted to USD ($)/ha in respective years following X-rates (2016).

$$\text{GR} = [(\text{Unit price} \times \text{grain yield}) + (\text{Unit price} \times \text{stover yield})] \quad (5)$$

$$\text{NR} = (\text{GR} - \text{total cost of a treatment}) \quad (6)$$

$$\text{NB : C} = [\text{NR}/(\text{Cost of a treatment})] \quad (7)$$

### *Statistical analysis*

The data were analysed using the 'analysis of variance (ANOVA) technique' as applicable to a randomized complete block design (both single-factor and three-factor analysis) as per the

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**Table 2.** Species-wise weed density (number/m$^2$ and per cent basis) at 30 DAS ($n = 8$) in the field in 2011 (Experiment 1)

| Botanical name | English name | Family | Habit | Density (No./m$^2$) | Relative density (%) |
|---|---|---|---|---|---|
| *Acrachne racemosa* (Heyne ex Roem and Schult) Ohwi | Goosegrass | Poaceae | Annual | 38 | 17.7 |
| *Commelina benghalensis* L. | Tropical spiderwort; Wandering Jaw | Commelinaceae | Annual | 10 | 4.7 |
| *Cyperus rotundus* L. | Purple nutsedge, nutsedge | Cyperaceae | Perennial | 84 | 39.1 |
| *Dactyloctenium aegyptium* (L.) P. Beauv. Willd. | Crowfoot grass | Poaceae | Annual | 12 | 5.6 |
| *Digera arvensis* (L.) Forsk. | False amaranth | Amaranthaceae | Annual | 16 | 7.4 |
| *Setaria viridis*(L.) Beauv. | Green foxtail | Poaceae | Annual | 18 | 8.4 |
| *Trianthema portulacastrum* L. | Horse purslane | Aizoaceae | Annual | 37 | 17.2 |
| Total | | | | 215 | 100 |

**Table 3.** Density and dry weight of different weeds categories and maize grain yield across the treatments at 60 DAS (Experiment I)

| | Weed density (no./m$^2$) | | | | Weed dry weight (g/m$^2$) | | | |
|---|---|---|---|---|---|---|---|---|
| Treatment | Broad-leaved | Grassy | *Cyperus rotundus* | Total[a] | Broad-leaved | Grassy | *Cyperus rotundus* | Total[a] |
| Atrazine + pendimethalin | 3.4[b] | 0.7[b] | 10.1[b] | 10.6[b] | 4.60[b] | 0.71[b] | 4.74[b] | 6.57[b] |
| Atrazine + HW | 2.9 | 2.9 | 8.8 | 9.7 | 4.22 | 4.06 | 3.49 | 6.75 |
| BM I | 3.4 | 6.8 | 4.8 | 8.9 | 3.90 | 6.87 | 2.76 | 8.31 |
| BM II | 2.9 | 6.2 | 4.5 | 8.1 | 3.63 | 6.02 | 1.95 | 7.22 |
| WC | 8.0 | 8.3 | 9.2 | 14.7 | 8.28 | 9.55 | 3.90 | 13.19 |
| WFC | 0.7 | 0.7 | 0.7 | 0.7 | 0.71 | 0.71 | 0.71 | 0.71 |
| LSD ($P \leqslant 0.05$) | 2.9 | 3.0 | 3.3 | 3.6 | 3.73 | 2.97 | 3.47 | 3.96 |

[a]The total weed densities/dry weights have been calculated by summing up the original values followed by $(x + 0.5)^{½}$ transformation.
[b]Square-root $(x + 0.5)^{½}$ transformed values. For details of treatments, see Experiment I in Table 1.

procedures described by Rangaswamy (2006). For Experiment II, the ANOVA was carried out for the 3-year period, considering year as a random effect. All data (weed, crop and soil parameters) were subjected to Kolmogorov–Smirnov and Levene tests for normality and homogeneity of variance. The uniformity in error variance was non-significant; hence, the data were pooled over the years. Weed data (density, dry weight) were subjected to square-root ($\sqrt{x + 0.5}$) transformation (Das, 1999), and analysed using ANOVA. The significance of difference among different treatments was tested by the variance ratio ($F$ test) at 5% level of significance ($P \leqslant 0.05$). Least significant difference (LSD) values were calculated for the parameters that exhibited significant difference. A linear regression analysis was done to work out the relationship between *Sesbania* biomass input and soil organic carbon/total soil nitrogen. A contrast analysis among treatments and controls (Experiment II) was performed using SAS 9.1 (SAS Institute, Cary, NC, USA).

## Results

### *Experiment I (weed control and maize growth and yield)*

Weed flora of the experimental maize field under WC situations (Table 2) comprised of three grassy weeds, namely, *Acrachne racemosa* (Heyne ex Roem and Schult) Ohwi., *Dactyloctenium aegyptium* (L.) P. Beauv. Willd. and *Setaria viridis* (L.) Beauv.; three BLWs, namely, *Trianthema portulacastrum* L., *Commelina benghalensis* L. and *Digera arvensis* (L.) Forsk.; and perennial sedge namely *C. rotundus* L. *Cyperus rotundus* was the most dominant weed (84 plants/m$^2$; 39.1%), followed by *A. racemosa* (Heyne ex Roem and Schult) Ohwi. (38 plants/m$^2$; 17.7%) and *T. portulacastrum* L. (37 plants/m$^2$; 17.2%). The other weed species, having <10% relative density, were of less importance in maize crop.

All the four weed control treatments being on par brought about a significant reduction in total weed density and weed dry weight compared to WC (Table 3). Lowest weed density (8.1 plants/m$^2$) was recorded with BM II (15 kg/ha *Sesbania* seed + 2,4-D 0.50 kg a.i./ha applied at 25 DAS along with pre-emergence pendimethalin), while lowest weed dry weight was recorded with Atrazine + HW. Atrazine + pendimethalin (tank-mix) resulted 100% control of grassy weeds but could not suppress the problematic sedge *C. rotundus*, which constituted 90.2% of the total weed population and 51.5% of the total weed dry weight. In contrast, BM II and BM I (10 kg/ha *Sesbania* seed + 2,4-D 0.50 kg a.i./ha applied at 25 DAS along with pre-emergence pendimethalin) displayed superior control of *C. rotundus* with approximately 50% reduction in weed density and 40%

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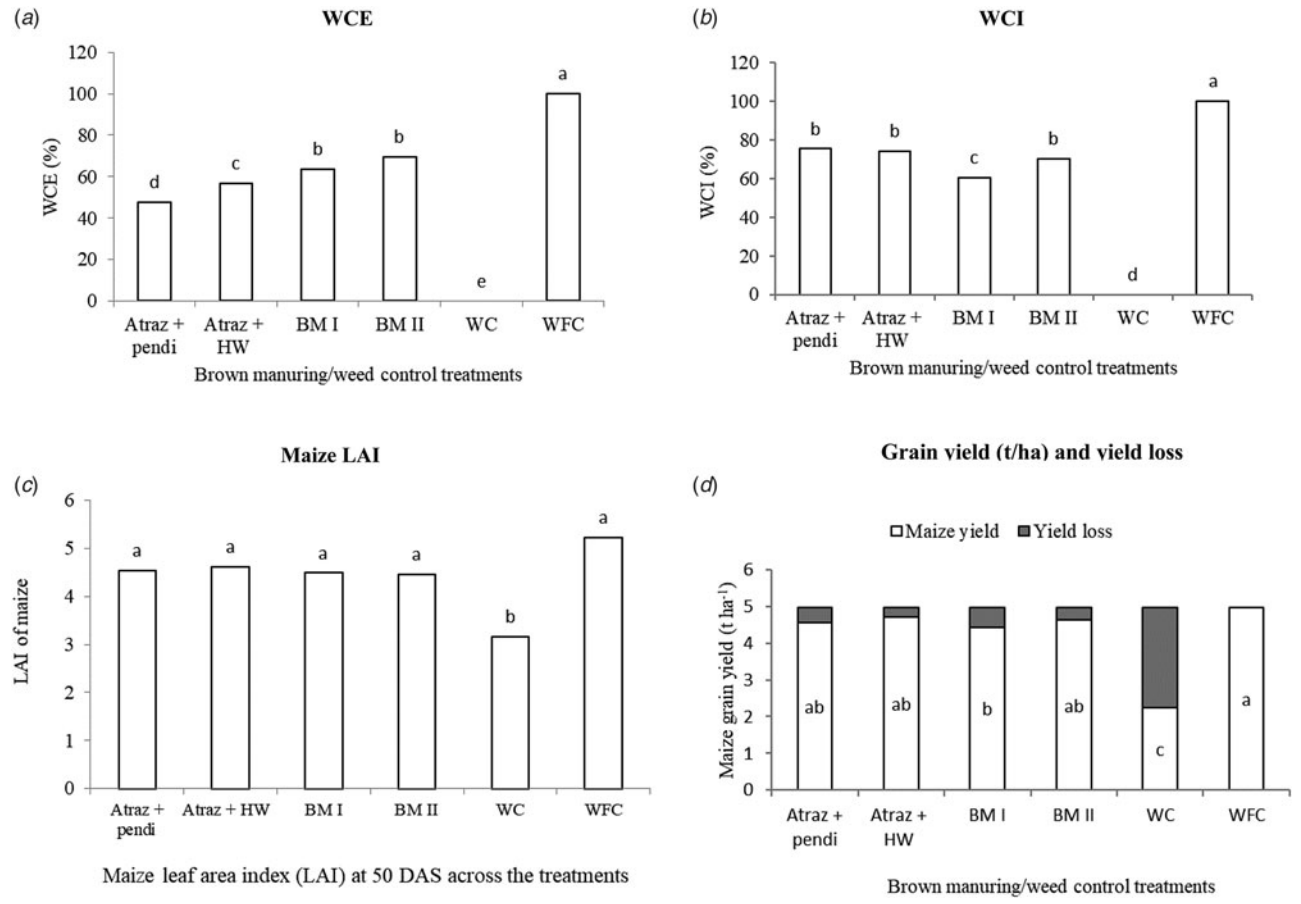



**Fig. 2.** (*a*) Weed control efficiency (WCE); (*b*) weed control index (WCI); (*c*) maize leaf area index (LAI) at 60 DAS and (*d*) maize grain yield and yield loss, across the treatments (Experiment I). Means with at least one letter common are not statistically significant at $P < 0.05$ (LSD).

**Table 4.** Combined analysis of variance for the studied parameters on weed growth, maize yield and economics (Experiment II)

| Contrast | DF | WD | WDM | GY | SY | WI | GR | NR | NB:C |
|---|---|---|---|---|---|---|---|---|---|
| Year (Y) | 2 | * | * | NS | * | NS | NS | NS | NS |
| R within Y | 6 | – | – | – | – | – | – | – | – |
| Seed rate (S) | 1 | * | * | * | * | * | * | * | * |
| Time (T) | 1 | * | * | * | * | * | * | * | * |
| Dose (D) | 1 | * | * | * | * | * | * | * | * |
| S × T | 1 | * | * | * | * | * | * | * | * |
| T × D | 1 | * | * | NS | NS | NS | NS | NS | NS |
| S × D | 1 | NS | NS | NS | NS | NS | NS | NS | NS |
| S × T × D | 1 | NS | NS | NS | NS | NS | NS | NS | NS |
| Control (C) | 2 | * | * | * | * | * | * | * | * |
| $C_1$ *v.* BM | 1 | NS | NS | * | * | * | * | * | * |
| $C_2$ *v.* BM | 1 | * | * | * | * | * | * | * | * |
| $C_3$ *v.* BM | 1 | * | * | * | * | * | * | NS | * |

R, replication; Y, year; $C_1$, herbicide control (atrazine + pendimethalin); $C_2$, weedy control; $C_3$, weed-free control; BM, brown manuring treatment mean ($T_1$ to $T_8$); DF, degrees of freedom; WD, total weed density (no./$m^2$); WDM, total weed dry matter (g/$m^2$); GY, maize grain yield (t/ha); SY, maize stover yield (t/ha); WI, weed index (%); GR, gross returns ($/ha); NR, net returns ($/ha); NB:C, net benefit:cost.

*Significant at $P \leqslant 0.05$; NS: non-significant; all other interactions (Y × S, Y × T, Y × D, Y × S × T, Y × T × D, Y × S × D, Y × S × T × D, Y × C and Y × $C_1/C_2/C_3$ *v.* BM) were non-significant for all the parameters.

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reduction in weed dry weight compared to the tank-mixture. BM II recorded a superior WCE (Fig. 2(*a*)) and WCI (Fig. 2(*b*)) being at par with atrazine + pendimethalin and atrazine + HW. Weed index, representing maize yield losses due to weeds (Fig. 2(*d*)), was significantly lower in atrazine + HW (5%), BM II (7%) and atrazine + pendimethalin (8%) compared to WC (~55%). The BM practice BM II being on par with the herbicide treatments recorded significantly higher LAI compared to WC (Fig. 2(*c*)) and gave high maize grain yields which were comparable to WFC (Fig. 2(*d*)).

## Experiment II

### Combined ANOVA for weed parameters, yield and economics

The effects of BM seed rate (S), time of 2,4-D application (T), dose of 2,4-D (D) and their interaction along with contrasts (BM *v.* controls) on weed parameters, maize yield and economics have been presented in combined ANOVA table (Table 4). Year effect was found significant for weed density, weed dry weight and maize stover yield. The main effects of *Sesbania* seed rate (S), dose (D) and time (T) of 2,4-D application, and the S × T interaction effects were significant for all the study parameters. The T × D interaction effect was significant only for weed density and weed dry weight. The interaction effects of S × D and S × T × D as well as all year (Y) × treatment interactions were non-significant for all the study parameters. The contrast atrazine + pendimethalin (control 1) *v.* BM (mean of eight BM treatments) was significant for all parameters except weed density and weed dry weight, indicating that BM was on par with the standard herbicide with respect to weed control. The other contrasts, *viz.*, $C_2$ (WC) *v.* BM and $C_3$ (WFC) *v.* BM, were significant for all the study parameters.

### Weed density, weed dry weight and control efficacy

At 60 DAS, the total weed density, weed dry weight and WCI differed significantly with *Sesbania* seed rate (S), time of 2,4-D application (T) and 2,4-D dose (D) (Table 4). Significantly lower weed density, dry weight and WCI were observed with S~25 kg/ha (3.9 plants/m$^2$, 4.52 g/m$^2$ and 84.2%, respectively) against S~15 kg/ha. Similarly, T~25 DAS (3.7 plants/m$^2$, 4.34 g/m$^2$ and 85.6%, respectively) was superior to T~35 DAS and D~0.50 kg a.i./ha (3.8 plants/m$^2$, 4.42 g/m$^2$ and 84.9%, respectively) over D~0.25 kg a.i./ha for the above-mentioned parameters (Table 5). The mean of BM ($T_1$ to $T_8$) treatments was on par to the standard herbicide atrazine + pendimethalin ($C_1$) in terms of weed density, weed dry weight and WCI. BM reduced weed density and weed dry weight by 62.7 and 58.3%, respectively, over WC. Overall, weed density and weed dry weight were higher during 2014 compared to 2013 and 2012. A single-factor analysis to compare the BM combinations (Table 6) confirmed that S~25 kg/ha + T~25 DAS + D~0.5 kg a.i/ha ($T_6$: $S_{25}$ $T_{25}$ $D_{0.50}$) and S~15 kg/ha + T~25 DAS + D~0.5 kg a.i./ha ($T_2$: $S_{15}$ $T_{25}$ $D_{0.50}$) led to significant reductions in weed dry weights (66.6 and 63.3%, respectively) compared to WC, and were superior to standard herbicide control. Under BM, *Sesbania* seed rate (S) × 2,4-D application time (T) and 2,4-D application time (T) × 2,4-D application dose (D) interaction effects were significant (Table 7), indicating that T levels responded differently to S and D levels, respectively, and *vice-versa*. Both S~15 and S~25 kg/ha registered significantly lower weed densities and weed dry weights at T~25 DAS against T~35 DAS. Similarly, 2,4-D application at 25 DAS as well as 35 DAS was more effective when a higher 2,4-D dose 0.50 kg a.i./ha was applied (Table 8).

**Table 5.** Density and dry weight of weeds and weed control index (WCI) at 60 DAS in maize in Experiment II (pooled mean of 3 years)

| Treatment/contrast | Weed density (no./m$^2$) | Weed dry weight (g/m$^2$) | WCI (%) |
|---|---|---|---|
| Year (Y) | | | |
| 2012 | 4.5[a] | 4.97[a] | 87.15 |
| 2013 | 4.6 | 5.26 | 86.75 |
| 2014 | 5.8 | 6.38 | 84.61 |
| LSD ($P \leqslant 0.05$) | 1.0 | 1.03 | 2.12 |
| *Sesbania* seed rate (S) | | | |
| 15 kg/ha | 4.3 | 4.89 | 81.4 |
| 25 kg/ha | 3.9 | 4.52 | 84.2 |
| LSD ($P \leqslant 0.05$) | 0.12 | 0.14 | 1.5 |
| Time of 2,4-D application (T) | | | |
| 25 DAS | 3.7 | 4.34 | 85.6 |
| 35 DAS | 4.5 | 5.08 | 80.1 |
| LSD ($P \leqslant 0.05$) | 0.12 | 0.14 | 1.5 |
| Dose of 2,4-D (D) | | | |
| 0.25 kg a.i./ha | 4.4 | 4.99 | 80.8 |
| 0.50 kg a.i./ha | 3.8 | 4.42 | 84.9 |
| LSD ($P \leqslant 0.05$) | 0.12 | 0.14 | 1.52 |
| Control (C) *v.* BM | | | |
| Atrazine + pendimethalin ($C_1$) | 4.0 | 4.56 | 84.2 |
| WC ($C_2$) | 11.0 | 11.32 | 0.0 |
| WFC ($C_3$) | 0.7 | 0.71 | 100.0 |
| BM ($n = 8$) | 4.1 | 4.71 | 82.8 |
| [b]LSD $(P \leqslant 0.05)_{Control}$ | 0.3 | 0.28 | 2.41 |
| [c]LSD $(P \leqslant 0.05)_{C1/C2/C3\ v.\ BM}$ | 0.3 | 0.30 | 2.53 |

BM, brown manuring treatment mean ($T_1$ to $T_8$).
[a]Square-root $(x + 0.5)^{1/2}$ transformed values. For details of treatments, see Experiment II in Table 1.
[b]LSD for pair-wise comparison among the controls (C1, C2, C3).
[c]LSD for pair-wise comparison between C1/C2/C3 *v.* BM.

### Yield and economics

Maize grain yields and yield losses due to weeds (WI) did not differ significantly between the years; however, stover yield was significantly higher in 2013 as compared to 2012 (Table 9). Factorial analysis of treatments revealed that despite being slightly inferior in terms of weed control, S~15 kg/ha returned 6.6% higher grain yield (5.01 t/ha) and 6.5% higher stover yield (7.64 t/ha) than S~25 kg/ha. Similarly, T~25 DAS resulted 4.2 and 4.3% higher grain and stover yields, respectively, over T~35 DAS, whereas D~0.50 kg a.i./ha resulted in ~4% higher grain and stover yields over D~0.25 kg a.i./ha. Although the standard herbicide check resulted in significantly superior maize grain yield (5.12 t/ha) compared to the overall BM yield (4.86 t/ha), it was inferior to the BM combination S~15 kg/ha + T~25 DAS + D~0.5 kg a.i./ha ($T_2$: $S_{15}$ $T_{25}$ $D_{0.50}$). The later registered a 3-year mean grain

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**Table 6.** One-way comparison/single-factor analysis using RCBD for the parameters of weeds and maize studied across treatments (pooled mean of 3 years)

| Treatment | Weed density (no./ $m^2$) | Weed dry weight ($g/m^2$) | WCI (%) | Grain yield (t/ha) | Stover yield (t/ha) | Cost of production ($/ha)[a] | Gross returns ($/ha)[a] | Net returns ($/ha)[a] | Net benefit: cost |
|---|---|---|---|---|---|---|---|---|---|
| $S_{15}$ $T_{25}$ $D_{0.25}$ ($T_1$) | 4.2[b] | 4.74[b] | 82.8 | 5.05 | 7.71 | 506 | 1335 | 829 | 1.64 |
| $S_{15}$ $T_{25}$ $D_{0.50}$ ($T_2$) | 3.4 | 4.15 | 86.9 | 5.25 | 8.01 | 510 | 1388 | 878 | 1.72 |
| $S_{15}$ $T_{35}$ $D_{0.25}$ ($T_3$) | 5.1 | 5.60 | 75.8 | 4.78 | 7.28 | 506 | 1262 | 756 | 1.49 |
| $S_{15}$ $T_{35}$ $D_{0.50}$ ($T_4$) | 4.5 | 5.08 | 80.2 | 4.97 | 7.58 | 510 | 1314 | 804 | 1.58 |
| $S_{25}$ $T_{25}$ $D_{0.25}$ ($T_5$) | 4.0 | 4.67 | 83.3 | 4.67 | 7.12 | 512 | 1234 | 722 | 1.41 |
| $S_{25}$ $T_{25}$ $D_{0.50}$ ($T_6$) | 3.1 | 3.78 | 89.2 | 4.86 | 7.40 | 516 | 1283 | 767 | 1.49 |
| $S_{25}$ $T_{35}$ $D_{0.25}$ ($T_7$) | 4.4 | 4.95 | 81.2 | 4.55 | 6.93 | 512 | 1202 | 690 | 1.35 |
| $S_{25}$ $T_{35}$ $D_{0.50}$ ($T_8$) | 4.1 | 4.68 | 83.3 | 4.73 | 7.21 | 516 | 1251 | 735 | 1.42 |
| Atrazine + pendimethalin ($T_9$) | 4.0 | 4.56 | 84.1 | 5.12 | 8.01 | 482 | 1361 | 879 | 1.82 |
| WC ($T_{10}$) | 11.0 | 11.32 | 0.0 | 2.58 | 3.83 | 446 | 677 | 231 | 0.52 |
| WFC ($T_{11}$) | 0.7 | 0.71 | 100.0 | 5.33 | 8.12 | 602 | 1408 | 806 | 1.34 |
| LSD ($P \leqslant 0.05$) | 0.2 | 0.28 | 1.6 | 0.15 | 0.11 | – | 34 | 34 | 0.07 |

For details of treatments, see Experiment II in Table 1.
[a]$(US Dollar) 1.0 = INR (Indian Rupee) 54.82 (2012), INR 62.59 (2013), INR 61.68 (2014).
[b]Square-root $(x + 0.5)^{½}$ transformed values.

**Table 7.** Interaction between *Sesbania* seed rate (S) × 2,4-D application time (T) on weed density, weed dry weight, maize grain yield and net returns

| Interaction effect (S × T) | | Weed density (no./$m^2$)[a] | Weed dry weight ($g/m^2$)[a] | Grain yield (t/ha) | Net returns ($/ha)[b] |
|---|---|---|---|---|---|
| *Sesbania* seed rate (S) | 2,4-D application time (T) | | | | |
| 15 kg/ha | 25 DAS | 3.8 | 4.45 | 5.15 | 854 |
| | 35 DAS | 4.8 | 5.34 | 4.87 | 780 |
| 25 kg/ha | 25 DAS | 3.5 | 4.23 | 4.76 | 745 |
| | 35 DAS | 4.2 | 4.82 | 4.64 | 712 |
| LSD ($P \leqslant 0.05$) | | 0.2 | 0.22 | 0.11 | 24 |

[a]Square-root $(x + 0.5)^{½}$ transformed values.
[b]See Table 10 for the value of $.

**Table 8.** Interaction between time (T) and dose (D) of application of 2,4-D on weed density and weed dry weight

| Interaction effect (T × D) | | | |
|---|---|---|---|
| 2,4-D application time (T) | 2,4-D application dose (D) | Weed density (no./$m^2$)[a] | Weed dry weight (g/$m^2$)[a] |
| 25 DAS | 0.25 kg a.i./ha | 4.1 | 4.71 |
| | 0.50 kg a.i./ha | 3.2 | 3.97 |
| 35 DAS | 0.25 kg a.i./ha | 4.7 | 5.28 |
| | 0.50 kg a.i./ha | 4.3 | 4.88 |
| LSD ($P \leqslant 0.05$) | | 0.2 | 0.22 |

[a]Square-root $(x + 0.5)^{½}$ transformed values.

and stover yield of 5.25 and 8.01 t/ha and was on par to the WFC. The yield response of *Sesbania* seed rate (S) differed with variation in 2,4-D application time (T) (Table 7). The yield of S~15 kg/ha significantly increased when 2,4-D was applied at 25 DAS (5.15 t/ha) against 35 DAS (4.87 t/ha) and similar was the case for S~25 kg/ha. The S × D and T × D and S × T × D interaction effects were non-significant for maize grain and stover yield.

The average cost of cultivation (Table 10) for BM ($511/ha) was marginally higher than standard herbicide atrazine + pendimethalin by 6% and WC by 15%, but lower than WFC by 15%. Atrazine + pendimethalin resulted in significantly higher gross ($1397/ha) and NR ($914/ha) as compared to the overall BM mean ($1284 and $773/ha, respectively). However, the BM combination S~15 kg/ha + T~25 DAS + D~0.5 kg a.i/ha ($T_2$: $S_{15}$ $T_{25}$ $D_{0.50}$) was comparable to the herbicide check with mean gross and NR of $1388/ha and $878/ha (9% higher than WFC), respectively, and a net B:C of 1.72 (Table 6). Factorial analysis revealed that the levels S~15 kg/ha, T~25 DAS and D~0.50 kg a.i./ha were superior to their respective counterparts with respect to above economic parameters (Table 10). A significant S × T interaction effect for NR was established (Table 7), with significant higher returns from S~25 kg/ha × T~25 DAS combination ($854/ha).

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**Table 9.** Grain and stover yields of maize and weed index (WI) across the treatments during 2012–2014 (Experiment II) (pooled mean of 3 years)

| Treatments | Grain yield (t/ha) | Stover yield (t/ha) | Weed index (%) |
|---|---|---|---|
| Year (Y) | | | |
| 2012 | 5.06 | 6.66 | 14.2 |
| 2013 | 4.45 | 7.79 | 14.0 |
| 2014 | 4.75 | 7.29 | 13.8 |
| LSD ($P \leqslant 0.05$) | NS | 1.08 | NS |
| *Sesbania* seed rate (S) | | | |
| 15 kg/ha | 5.01 | 7.64 | 5.9 |
| 25 kg/ha | 4.70 | 7.17 | 11.7 |
| LSD ($P \leqslant 0.05$) | 0.08 | 0.05 | 1.41 |
| Time of 2,4-D application (T) | | | |
| 25 DAS | 4.96 | 7.56 | 6.9 |
| 35 DAS | 4.76 | 7.25 | 10.7 |
| LSD ($P \leqslant 0.05$) | 0.8 | 0.05 | 1.4 |
| Dose of 2,4-D (D) | | | |
| 0.25 kg a.i./ha | 4.76 | 7.26 | 10.6 |
| 0.50 kg a.i./ha | 4.95 | 7.55 | 7.0 |
| LSD ($P \leqslant 0.05$) | 0.08 | 0.05 | 1.4 |
| Control (C) *v.* BM | | | |
| Atrazine + pendimethalin ($C_1$) | 5.12 | 8.01 | 3.9 |
| WC ($C_2$) | 2.58 | 3.83 | 51.7 |
| WFC ($C_3$) | 5.33 | 8.12 | 0.0 |
| BM ($N = 8$) | 4.86 | 7.40 | 8.8 |
| [a]LSD $(P \leqslant 0.05)_{Control}$ | 0.15 | 0.11 | 2.8 |
| [b]LSD $(P \leqslant 0.05)_{C1/C2/C3\ v.\ BM}$ | 0.16 | 0.12 | 3.0 |

For details of treatments, see Experiment II in Table 1.
BM, brown manuring treatment mean ($T_1$ to $T_8$).
[a]LSD for pair-wise comparison among the controls (C1, C2, C3).
[b]LSD for pair-wise comparison between C1/C2/C3 *v.* BM.

## Discussion

### Sesbania–*maize interaction*

For BM practice to be effective, the *Sesbania* interference should be minimized for the crop through proper optimization of *Sesbania* seed rate, and time and dose of 2,4-D application. *Sesbania* stimulates the crop growth through formation of a dead mulch (brown manure) while aids in conserving moisture, moderating temperature and improving soil physical, chemical and biological properties. The depths of seeding of *Sesbania* and maize, and moisture availability on the surface soil (0–0.03 m) after sowing created differences in the time of emergence of weeds (in 4 days), *Sesbania* (in 3 days) and maize (in 5 days). *Sesbania* with a shorter emergence time (owing to the nature of seeds and seed coats) had a competitive advantage over maize and weeds through early space capture. All BM treatments were supplemented with the herbicide pendimethalin, which eliminated initial interference from annual weeds. During initial 10 DAS, there was no visible interference of *Sesbania* to maize crop since maize plants with 2–3 fully-grown leaves had larger sized canopy compared to *Sesbania*. However, maize had much lower plant population (10–14 plants/$m^2$) compared to *Sesbania* populations (~45–60 plants/$m^2$ at 1.5 g seed/$m^2$; 75–100 plants/$m^2$ at 2.5 g seed/$m^2$). At 17–18 DAS onwards, *Sesbania* manifested substantially higher crop growth rate and canopy coverage and created interference for space (i.e. space limitation), owing to which maize plants became slender, taller and almost in similar height as that of *Sesbania* plants. The biotic interference between maize, *Sesbania* and weeds, however, was not prolonged due to killing of *Sesbania* at 25 DAS by applying 2,4-D. Interference was prolonged when *Sesbania* was killed at 35 DAS, which offered a more negative impact on weeds as well as on maize (discussed later). Thus, *Sesbania* plants served as a live mulch for the initial 25/35 DAS and as a dead mulch after being killed by 2,4-D, and continued to smother weeds for the initial 35/45 DAS, depending on BM treatments. Later, a vigorous canopy cover of maize could suppress the weeds better.

### *Impacts on weed interference in maize*

We attempted to evaluate the dual role of BM (initial interference against weed and later stimulation to crop) in maize through a series of trials under two experiments (2011–2014). In Experiment I (Table 3), BM II involving 15 kg/ha *Sesbania* seed + 2,4-D 0.50 kg a.i./ha applied at 25 DAS along with pendimethalin (PE) registered highest reduction in total weed density (WCE 70%) with superior control of BLWs (~63.7%) and *C. rotundus* (51.0%), but poor control of grasses (25.3%) compared to WC. Particularly, *Sesbania* BM (BM I and BM II) exhibited significant superior control of the problematic weed *C. rotundus*, which was rampant in the atrazine + pendimethalin and atrazine + HW treatments with 90.2 and 82.7%, respectively, of the total weed density. The weed dry weight, a more reliable estimate of weed interference than weed density (Das, 2001), was lowest in the treatment atrazine + pendimethalin tank-mixture (WCI 75%), but was statistically comparable to BM II and BM I. The positive outcome from BM treatments with respect to weed management encouraged us to conduct a second and elaborative experiment (Experiment II) employing a higher seed rate of *Sesbania* (25 kg/ha) with an extended date of *Sesbania* killing (35 DAS) for optimization of BM in maize crop.

During Experiment II, initial higher rainfall during the first 3 weeks after sowing in 2013 and 2014 affected the efficacy of pendimethalin (pre-emergence) applied to BM treatments (Fig. 1(*b*)). Two BM treatments, $T_6$ (25 kg/ha *Sesbania* seed + 2,4-D 0.50 kg a.i./ha applied at 25 DAS) and $T_2$ (15 kg/ha *Sesbania* seed + 2,4-D 0.50 kg a.i./ha applied at 25 DAS) caused greater reduction in weed density (71.8 and 69%, respectively) and weed dry weight (66.6 and 63.3%, respectively) compared to WC and were statistically superior to the herbicide check atrazine + pendimethalin tank-mixture ($T_9$). Factorial analysis (Table 4) segregated the BM treatment effects into individual contrasts, *viz.*, seed rate (S), 2,4-D application time (T) and 2,4-D dose (D). It revealed that T (25 DAS > 35 DAS) and D (0.50 kg a.i./ha > 0.25 kg a.i./ha) had greater impacts on weed suppression compared to S (25 kg/ha > 15 kg/ha) as found from their *F* ratios. The higher *Sesbania* populations, resulting from higher seed rate offered slightly better weed suppression owing to enhanced smothering effects. 2,4-D showed higher efficacy when applied at 25 rather than 35 DAS, since *Sesbania* and weeds were relatively younger and smaller at 25 DAS and, therefore, more susceptible. 2,4-D

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**Table 10.** Economics of maize production across the treatments in Experiment II (pooled mean of 3 years)

| Treatment/contrast | Cost of production ($/ha)[a] | Gross returns ($/ha)[a] | Net returns ($/ha)[a] | Net benefit: cost (NB:C) |
|---|---|---|---|---|
| Year (Y) | | | | |
| 2012 | 504 | 1321 | 817 | 1.63 |
| 2013 | 459 | 1124 | 665 | 1.58 |
| 2014 | 541 | 1237 | 696 | 1.30 |
| LSD ($P \leqslant 0.05$) | – | NS | NS | NS |
| *Sesbania* seed rate (S) | | | | |
| 15 kg/ha | 508 | 1325 | 817 | 1.61 |
| 25 kg/ha | 514 | 1242 | 728 | 1.42 |
| LSD ($P \leqslant 0.05$) | – | 17 | 17 | 0.03 |
| Time of 2,4-D application (T) | | | | |
| 25 DAS | 511 | 1310 | 799 | 1.56 |
| 35 DAS | 511 | 1257 | 746 | 1.46 |
| LSD ($P \leqslant 0.05$) | – | 17 | 17 | 0.03 |
| Dose of 2,4-D (D) | | | | |
| 0.25 kg a.i./ha | 509 | 1258 | 749 | 1.47 |
| 0.50 kg a.i./ha | 513 | 1309 | 796 | 1.55 |
| LSD ($P \leqslant 0.05$) | – | 17 | 17 | 0.03 |
| Control (C) *v.* BM | | | | |
| Atrazine + pendimethalin ($C_1$) | 482 | 1361 | 879 | 1.82 |
| WC ($C_2$) | 446 | 677 | 231 | 0.52 |
| WFC ($C_3$) | 602 | 1408 | 806 | 1.34 |
| BM ($N = 8$) | 511 | 1284 | 773 | 1.51 |
| [b]LSD ($P \leqslant 0.05$)$_{Control}$ | – | 34 | 34 | 0.07 |
| [c]LSD ($P \leqslant 0.05$)$_{C1/C2/C3\ v.\ BM}$ | – | 36 | 36 | 0.07 |

BM, brown manuring treatment mean ($T_1$ to $T_8$).
[a]$(US Dollar) 1.0 = INR (Indian Rupee) 54.82 (2012), INR 62.59 (2013), INR 61.68 (2014). For details of treatments, see Experiment II in Table 1.
[b]LSD for pair-wise comparison among the controls (C1, C2, C3).
[c]LSD for pair-wise comparison between C1/C2/C3 *v.* BM.

killed *Sesbania* and BLWs effectively and *C. rotundus* moderately, but grassy weeds were spared due to its narrow-spectrum activity at both 25 and 35 DAS. Higher dose-effect of 2,4-D led to better weed control at 0.50 than 0.25 kg a.i./ha. However, a selective broad-spectrum herbicide (presently lacking) in place of 2,4-D might be better. In all BM treatments, pendimethalin controlled initial infestations of dominant annual weeds, mainly, *T. portulacastrum* and *A. racemosa*, and helped *Sesbania* and maize to emerge in almost weed-free conditions and to smother late-emerging weeds better.

The tank-mixture consisted of atrazine (a photosystem II inhibitor) and pendimethalin (a microtubule assembly inhibitor). Atrazine killed most annual BLWs and few monocot grassy weeds, including *D. arvensis* (BLW), not controlled by pendimethalin (Susha *et al.*, 2014). Pendimethalin killed most annual monocot grassy weeds including *A. racemosa* and few BLWs including *T. portulacastrum* (mentioned above). Two different modes of action and better compatibility of these herbicides in tank-mixture led to an effective control of annual weeds, but not perennial *C. rotundus* (Experiment I). BM suppressed *C. rotundus* better than the tank-mixture in which the weed existed with 90.2% density and 51.5% dry weight of total weeds (Table 3). *Cyperus rotundus* shows tolerance to almost all herbicides used for maize. Practicing BM (biological intervention) and application of pre-emergence pendimethalin (chemical intervention) has been found to reduce the preponderance of *C. rotundus*, and lead to a better weed management.

### *Impacts on maize yield and economics*

Maize grain yields and yield losses due to weeds did not differ significantly across years; however, stover yields were significantly higher in 2013 compared to 2012 (Table 9). This might have been due to narrower variations ($T_{max} - T_{min}$) in daily temperatures (Fig. 1(*a*)) due to consistently higher daily minimum temperatures during mid-September to mid-October in 2013, accompanied by intermittent showers (Fig. 1(*b*)). This promoted higher vegetative growth but lower grain filling of maize. Higher rainfall (~1196.6 mm) in 2013 resulted in periodic water-logging, to which maize was susceptible (Dass *et al.*, 2008), and consequently reduced the grain yield.

Among all the BM treatments, 15 kg/ha *Sesbania* seed + 2,4-D 0.50 kg a.i./ha applied at 25 DAS ($T_2$) secured higher grain yield than atrazine + pendimethalin tank-mixture (Table 6). Superior

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performance of $T_2$ could be due to combined effects of superior WCE (~69%), lesser *Sesbania*–crop interference due to lower seed rate (compared to S~25 kg/ha) and an improved microclimate and soil properties (SOC and TSN) through *Sesbania* biomass addition. In this BM practice, initial temporary interference (at pre-killing period for 25 DAS) offered by the *Sesbania* live cover on maize might be largely compensated/mitigated by the vigorously growing maize plants at *Sesbania* post-killing period. Comparable LAI of maize plants obtained under the BM II (Experiment I) with atrazine + pendimethalin and WFC treatments could substantiate this fact (Fig. 2(*c*)). *Sesbania* biomass after 2,4-D application acted as a decomposing mulch, which might stimulate maize growth through conserving moisture (Sharma *et al.*, 2010*a*, 2010*b*), accumulating soil C and N (Sharma *et al.*, 2010*a*, 2010*b*), moderating temperature and reducing erosion (Lal, 1997, 2004; Singh *et al.*, 2005; Verhulst *et al.*, 2011; Ram *et al.*, 2012). Not studied, but innumerable castings of earthworms found in BM plots (Authors' observations) indicate its effects on earthworms, and possibly, on soil micro flora/fauna. These reflected the superiority of this BM to a purely chemical method (i.e. atrazine + pendimethalin). The biological systems are resilient and can readily adjust to a change in crop plant micro-climate through capturing space and responding more to available growth factors as in case for $T_2$. However, the treatment $T_6$, having higher *Sesbania* population (25 kg seed/ha), suppressed weeds better and simultaneously offered greater interference to maize, which was not fully compensated at *Sesbania* post-killing period, resulting in lower yield and NR.

All BM treatments (Table 6) due to an additional application of pendimethalin and seed cost of *Sesbania* incurred higher cost than the atrazine + pendimethalin. But they had a lower cost than WFC. The superior BM combination $S_{15}$ $T_{25}$ $D_{0.50}$ ($T_2$) gave higher GR ($1388/ha) than the tank-mixture of atrazine + pendimethalin ($1361/ha), but owing to a higher cost of cultivation, their NR were equivalent. However, compared to WFC, the cost of $T_2$ was lower by $92.0 (~15.3%) and NR higher by $72.0 (~9.0%). Thus, the $T_2$ was found to be an economically superior alternative to WFC and environmentally superior alternative to the recommended tank-mixture of atrazine + pendimethalin.

## Conclusions

The *Sesbania* seed rate and the time and dose of 2,4-D application, which are three important requirements for the successful adoption of BM in maize, were optimized in this study. A BM practice, involving 15 kg/ha *Sesbania* seed + 2,4-D at 0.50 kg a.i./ha applied at 25 DAS along with a pre-emergence application of pendimethalin 1.0 kg a.i./ha could lead to an effective weed management in maize. This BM practice was comparable with the herbicide control (i.e. atrazine + pendimethalin) on the reduction of weed population and dry weight. It also led to a better control of the noxious weed *C. rotundus* than the herbicide control and gave higher grain and stover yields of maize and NR. It can be recommended for the North-western Indo-Gangetic Plains of India and in similar agro-ecologies of the tropics and sub-tropics. Further studies of its impacts on the soil physico-chemical and biological properties, and greenhouse gases emissions across maize varieties grown in particular situations may reveal other sustainability benefits accruing from it and widen its adoption/application.

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## References

**Asres B and Das TK** (2011) Diversity and integrated management of weeds in highland wheat of Northern Ethiopia. *Plant Protection Quarterly* **26**, 8–16.

**Behera B, Das TK, Ghosh S, Kaur R and Singh R** (2018) Brown manuring in maize (*Zea mays*): effects on weed interference and crop productivity. *Indian Journal of Agronomy* **63**, 524–527.

**Bhattacharyya R, Das TK, Pramanik P, Ganeshan V, Saad AA and Sharma AR** (2013) Impacts of conservation agriculture on soil aggregation and aggregate-associated N under irrigated agroecosystem of Indo-Gangetic Plains. *Nutrient Cycling in Agroecosystems* **96**, 185–202.

**Bhattacharyya R, Das TK, Sudhishri S, Dudwal B, Sharma AR, Bhatia A and Singh G** (2015) Conservation agriculture effects on soil organic carbon accumulation and crop productivity under a rice–wheat cropping system in the western Indo-Gangetic Plains. *European Journal of Agronomy* **70**, 11–21.

**Das TK** (1999) Is transformation of weed data always necessary?. *Annals of Agricultural Research* **20**, 335–341.

**Das TK** (2001) Towards better appraisal of herbicide bio-efficacy. *Indian Journal of Agricultural Sciences* **71**, 676–678.

**Das TK and Yaduraju NT** (2011) Effects of missing-row sowing supplemented with row spacing and nitrogen on weed interference and growth and yield of wheat. *Crop & Pasture Science* **62**, 48–57.

**Das TK, Bhattacharyya R, Sharma AR, Das S, Saad AA and Pathak H** (2013) Impacts of conservation agriculture on total soil organic carbon retention potential under an irrigated agro-ecosystem of the western Indo-Gangetic Plains. *European Journal of Agronomy* **51**, 34–42.

**Das TK, Ahlawat IPS and Yaduraju NT** (2014*a*) Littleseed canarygrass (*Phalaris minor*) resistance to clodinafop-propargyl in wheat fields in north-western India: appraisal and management. *Weed Biology and Management* **14**, 11–20.

**Das TK, Paul AK and Yaduraju NT** (2014*b*) Density-effect and economic threshold of purple nutsedge (*Cyperus rotundus*) in soybean. *Journal of Pest Science* **87**, 211–220.

**Das TK, Saharawat YS, Bhattacharyya R, Sudhishri S, Bandyopadhyay KK, Sharma AR and Jat ML** (2018) Conservation agriculture effects on crop and water productivity, profitability and soil organic carbon accumulation under a maize-wheat cropping system in the North-western Indo-Gangetic Plains. *Field Crops Research* **215**, 222–231.

**Dass S, Jat ML, Singh KP and RAI HK** (2008) Agro-economic analysis of maize based cropping system in India. *Indian Journal of Fertilizers* **4**, 49–62.

**Gangaiah B and Babu MBB** (2016) Brown manuring as a tool of weed management and contributor to nitrogen nutrition of direct wet seeded rice. *ORYZA – An International Journal on Rice*, **53**, 415–421.

**Gilreath JP and Santos BM** (2004) Efficacy of methyl bromide alternatives on purple nutsedge control (*Cyperus rotundus*) in tomatoes and peppers. *Weed Technology* **18**, 141–145.

**Gupta RK and Seth A** (2007) A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic plains (IGP). *Crop Protection* **26**, 436–447.

**Jackson ML** (1973) *Soil Chemical Analysis*. New Delhi, India: Prentice Hall of India Limited.

**Jalota SK, Buttar GS, Sood A, Chahal GBS, Ray SS and Panigrahy S** (2008) Effects of sowing date tillage and residue management on productivity of cotton (*Gossypium hirsutum* L.)–wheat (*Triticum aestivum* L.) system in northwest India. *Soil and Tillage Research* **99**, 77–83.

**Kumar M, Das TK and Yaduraju NT** (2012) An integrated approach for management of *Cyperus rotundus* (purple nutsedge) in soybean-wheat cropping system. *Crop Protection* **33**, 74–81.

https://doi.org/10.1017/S0021859620000064 Published online by Cambridge University Press

**Ladha JK, Kumar V, Alam MM, Sharma S, Gathala MK, Chandra P, Saharawat YS, Balasubramanian V** (2009) Integrating crop and resource management technologies for enhanced productivity, profitability and sustainability of the rice–wheat system in South Asia. In Ladha JK, Singh Y, Erenstein O and Hardy B (eds), *Integrated Crop and Resource Management in the Rice–Wheat System of South Asia*. Los Banos, Philippines: IRRI and Asian Development Bank, pp. 69–108.

**Lal R** (1997) Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by $CO_2$-enrichment. *Soil and Tillage Research* **43**, 81–107.

**Lal R** (2004) Soil carbon sequestration to mitigate climate change. *Geoderma* **123**, 1–22.

**Maitra S and Zaman A** (2017) Brown manuring, an effective technique for yield sustainability and weed management of cereal crops: a review. *International Journal of Bioresource Science* **4**, 1–5.

**Nath CP, Das TK and Rana KS** (2016) Effects of herbicides and tillage practices on weeds and summer mungbean (*Vigna radiata*) in wheat (*Triticum aestivum*)-mungbean cropping sequence. *Indian Journal of Agricultural Sciences* **86**, 860–864.

**Nawaz A, Farooq M, Lal R, Rehman A, Hussain T and Nadeem A** (2017) Influence of *Sesbania* brown manuring and rice residue mulch on soil health, weeds and system productivity of conservation rice–wheat systems. *Land Degradation and Development* **28**, 1078–1090.

**Olsen BC, Cole CV, Watenabe FS and Dean LA** (1954) *Estimation of Available Phosphorus by Extraction with Sodium Carbonate*. Washington, USA: USDA, p. 19.

**Oyeogbe AI, Das TK, Bhatia A and Singh SB** (2017) Adaptive nitrogen and integrated weed management in conservation agriculture: impacts on agronomic productivity, greenhouse gas emissions, and herbicide residues. *Environmental Monitoring and Assessment* **189**, 198.

**Pandey AK, Prakash V, Singh RD and Mani VP** (2001) Integrated weed management in maize (*Zea mays*). *Indian Journal of Agronomy* **46**, 260–265.

**Ram H, Singh Y, Saini KS, Kler DS, Timsina J and Humphreys EJ** (2012) Agronomic and economic evaluation of permanent raised beds, no tillage and straw mulching for an irrigated maize–wheat system in northwest India. *Experimental Agriculture* **48**, 21–38.

**Ramachandran A, Veeramani A and Prema P** (2012) Effect of brown manuring on weed growth, yield and economics of irrigated maize. *Indian Journal of Weed Science* **44**, 204–206.

**Rangaswamy R** (2006) *A Text Book of Agricultural Statistics*. New Delhi, India: New Age International.

**Saad AA, Das TK, Rana DS, Sharma AR, Bhattacharyya R and Lal K** (2016) Energy auditing of maize-wheat-greengram cropping system under conventional and conservation agriculture in irrigated North-western Indo-Gangetic Plains. *Energy* **116**, 293–305.

**Sen A, Singh SC, Sharma SN, Singh AK, Singh R and Pal AK** (2000). Agronomy of maize inbred parental line. *Indian Farming* **1**, 18–20.

**Sharma AR, Singh R, Dhyani SK and Dube RK** (2010*a*) Effect of live mulching with annual legumes on performance of maize (*Zea mays*) and residual effect on following wheat (*Triticum aestivum*). *Indian Journal of Agronomy* **55**, 177–183.

**Sharma AR, Singh R, Dhyani SK and Dube RK** (2010*b*) Moisture conservation and nitrogen recycling through legume mulching in rainfed maize (*Zea mays*)–wheat (*Triticum aestivum*) cropping system. *Nutrient Cycling in Agroecosystems* **87**, 187–197.

**Sharma AR, Singh R, Dhyani SK and Dube RK** (2011) Agronomic and economic evaluation of mulching in rainfed maize-wheat cropping system in the Western Himalayan Region of India. *Journal of Crop Improvement* **25**, 392–408.

**Singh Y, Singh B and Timsina J** (2005) Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. *Advances in Agronomy* **85**, 269–407.

**Singh S, Ladha JK, Gupta RK, Rao AN and Singh PP** (2007) Evaluation of mulching, intercropping with *Sesbania* and herbicides use for weed management in dry seed rice (*Oryza sativa* L.). *Crop Protection* **26**, 518–524.

**Singh S, Chhokar RS, Gopal R, Ladha JK, Gupta RK, Kumar V, Singh M** (2009) Integrated weed management: a key to success for direct-seeded rice in the Indo-Gangetic plains. In Ladha JK, Singh Y, Erenstein O and Hardy B (eds), *Integrated Crop and Resource Management in the Rice–Wheat System of South Asia*. Los Banos, Philippines: IRRI and Asian Development Bank, pp. 261–278.

**Singh S, Walia US, Kaur R and Shergill LS** (2010) Chemical control of *Cyperus rotundus* in maize. *Indian Journal of Weed Science*, **42**, 189–192.

**Subbiah BV and Asija GL** (1956) A rapid procedure for the estimation of available nitrogen in soils. *Current Science* **25**, 259–260.

**Susha VS, Das TK and Sharma AR** (2014) Weed management in maize (*Zea mays*) in western Indo-Gangetic Plains through tank-mix herbicide application. *Indian Journal of Agricultural Sciences* **84**, 1363–1368.

**Susha VS, Das TK, Nath CP, Pandey R, Paul S and Ghosh S** (2018) Impacts of tillage and herbicide mixture on weed interference, agronomic productivity and profitability of a maize–wheat system in the North-western Indo-Gangetic Plains. *Field Crops Research* **219**, 180–191.

**Tuti MD and Das TK** (2011). Sequential application of metribuzin on weed control, growth and yield of soybean (*Glycine max*). *Indian Journal of Agronomy* **56**, 57–61.

**Verhulst N, Kienle F, Sayre KD, Deckers J, Raes D, Limon-Ortega A, Tijerina-Chavez L and Govaerts B** (2011) Soil quality as affected by tillage-residue management in a wheat-maize irrigated bed planting system. *Plant and Soil* **340**, 453–466.

**Walkley A and Black IA** (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of chromic acid titration method. *Soil Science* **37**, 29–38.

**X-RATES** (2016) Exchange rates. Available at https://xrates.com/average/from=INR&to=USD (Accessed 7 December 2016).

https://doi.org/10.1017/S0021859620000064 Published online by Cambridge University Press