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

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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. S₂₅T₂₅D_{0.50}) resulted in lowest weed density (3.1/m²) and dry weight (3.8 g/m²) and highest weed control index (89.2%) at 60 days after sowing (DAS) which was at par with another BM practice S₁₅T₂₅D_{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.*, 2010a; Ramachandran *et al.*, 2012; Das *et al.*, 2014a). Besides, *in situ* *Sesbania* biomass like other residues can conserve soil moisture (Lal, 1997; Sharma *et al.*, 2010a, 2010b) and reduce irrigation

water requirement, sequester C and N in the soil (Singh et al., 2005; Sharma et al., 2010a, 2010b; 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., 2010a, 2010b, 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/m²) 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., 2014b), 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 Haplustep) 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 P₂O₅/ha (Olsen et al., 1954) and 250.5 kg K₂O/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 (T₁ to T₈) with three controls (T₉, T₁₀ and T₁₁). 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,

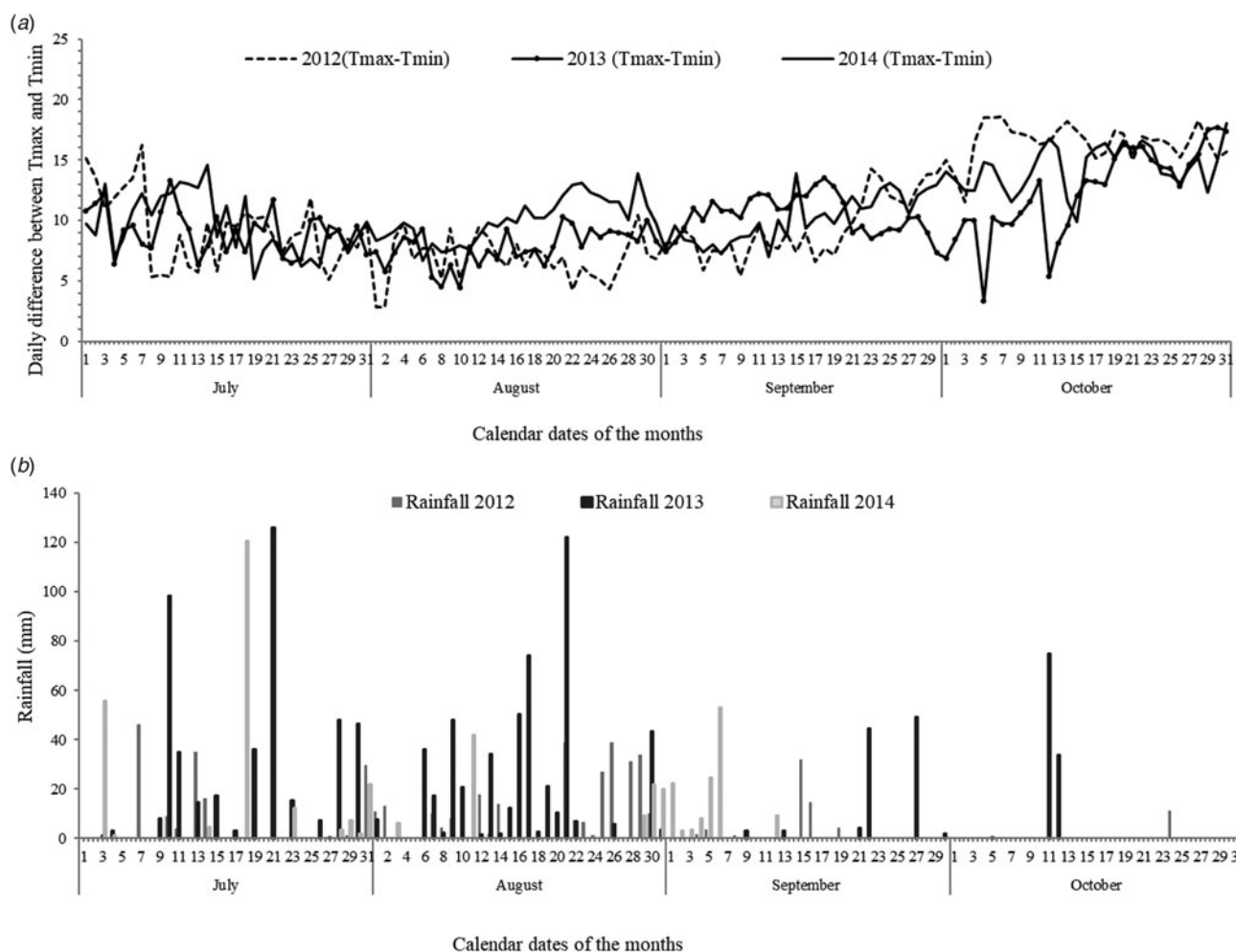


Fig. 1. Temperature (°C) and rainfall (mm) during 2012, 2013 and 2014 in maize: (a) daily differences between maximum (Tmax) and minimum (Tmin) temperatures; (b) daily rainfall (mm).

whereas five irrigations were given in 2013 in all treatments. A recommended dose of 120 kg N, 60 kg P₂O₅ and 40 kg K₂O 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).

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

where WP_c and WP_t are the weed density (no./m²) 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).

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

where WD_c and WD_t are the weed dry weights (g/m²) 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).

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

where Y_{wf} and Y_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

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 <i>Sesbania aculeata</i> 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. <i>Sesbania</i> seeds were broadcast at the time of sowing of maize. Killing and drying of <i>Sesbania</i> plants served as live and dead mulch for initial 35–40 DAS}	BM I
Brown manuring with <i>Sesbania aculeata</i> 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) <i>Sesbania</i> 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 <i>Sesbania</i> 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 <i>Sesbania</i> 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 <i>Sesbania</i> 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) <i>Sesbania</i> 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 <i>Sesbania</i> 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 <i>Sesbania</i> 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 <i>Sesbania</i> 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)

^aIn 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).

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

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).

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

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

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

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

Table 2. Species-wise weed density (number/m² 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 (%)
<i>Acrachne racemosa</i> (Heyne ex Roem and Schult) Ohwi	Goosegrass	Poaceae	Annual	38	17.7
<i>Commelina benghalensis</i> L.	Tropical spiderwort; Wandering Jaw	Commelinaceae	Annual	10	4.7
<i>Cyperus rotundus</i> L.	Purple nutsedge, nutsedge	Cyperaceae	Perennial	84	39.1
<i>Dactyloctenium aegyptium</i> (L.) P. Beauv. Willd.	Crowfoot grass	Poaceae	Annual	12	5.6
<i>Digera arvensis</i> (L.) Forsk.	False amaranth	Amaranthaceae	Annual	16	7.4
<i>Setaria viridis</i> (L.) Beauv.	Green foxtail	Poaceae	Annual	18	8.4
<i>Trianthema portulacastrum</i> 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)

Treatment	Weed density (no./m ²)				Weed dry weight (g/m ²)			
	Broad-leaved	Grassy	<i>Cyperus rotundus</i>	Total ^a	Broad-leaved	Grassy	<i>Cyperus rotundus</i>	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 ($P \leq 0.05$)	2.9	3.0	3.3	3.6	3.73	2.97	3.47	3.96

^aThe total weed densities/dry weights have been calculated by summing up the original values followed by $(x+0.5)^{1/2}$ transformation.

^bSquare-root $(x+0.5)^{1/2}$ 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 ($P \leq 0.05$). 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/m²; 39.1%), followed by *A. racemosa* (Heyne ex Roem and Schult) Ohwi. (38 plants/m²; 17.7%) and *T. portulacastrum* L. (37 plants/m²; 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/m²) 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%

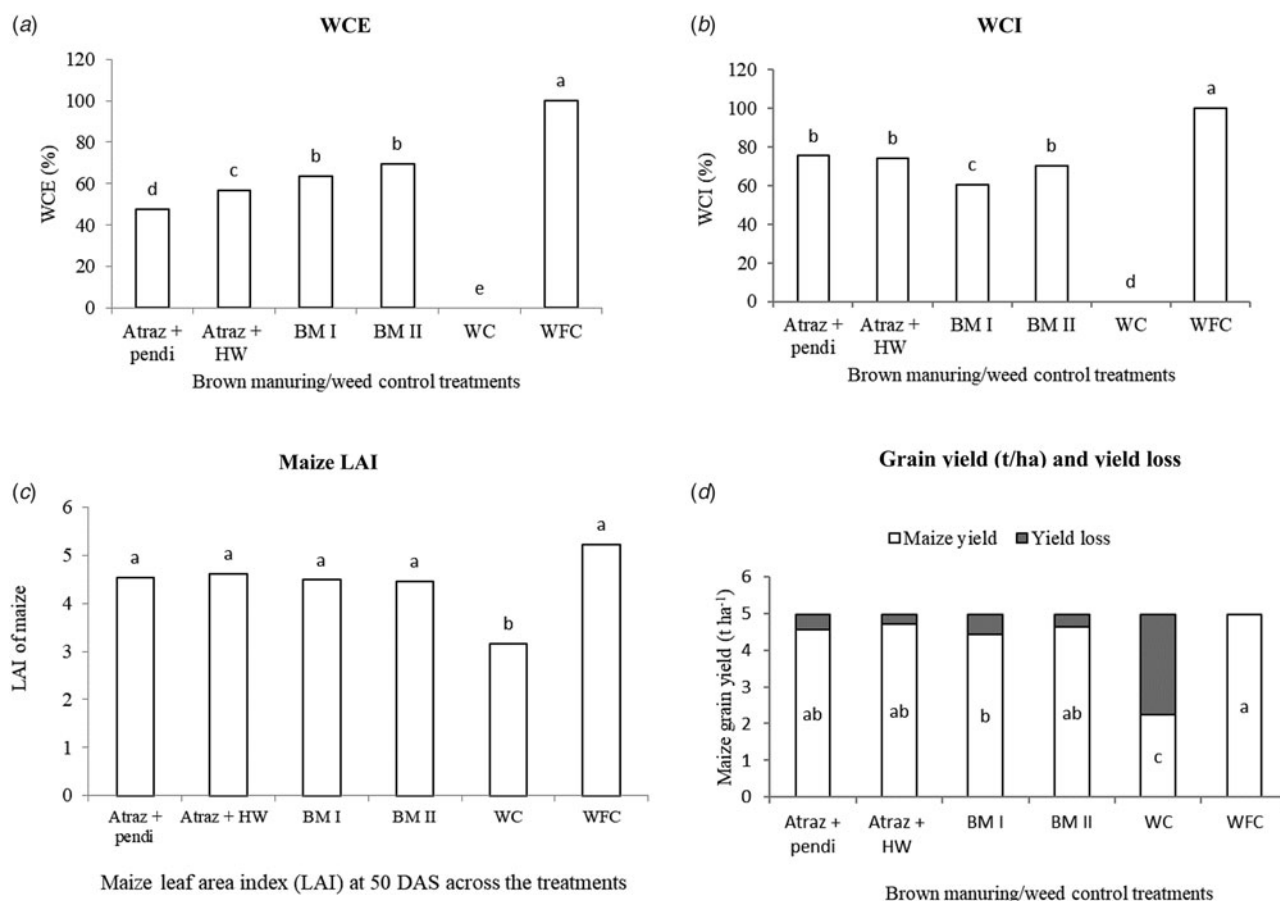


Fig. 2. (a) Weed control efficiency (WCE); (b) weed control index (WCI); (c) maize leaf area index (LAI) at 60 DAS and (d) maize grain yield and yield loss, across the treatments (Experiment I). Means with at least one letter common are not statistically significant at $P < 0.05$ (LSD).

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; C₁, herbicide control (atrazine + pendimethalin); C₂, weedy control; C₃, weed-free control; BM, brown manuring treatment mean (T₁ to T₈); DF, degrees of freedom; WD, total weed density (no./m²); WDM, total weed dry matter (g/m²); 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 $P \leq 0.05$; 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 × C₁/C₂/C₃ v. BM) were non-significant for all the parameters.

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., C₂ (WC) v. BM and C₃ (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/m², 4.52 g/m² and 84.2%, respectively) against S~15 kg/ha. Similarly, T~25 DAS (3.7 plants/m², 4.34 g/m² and 85.6%, respectively) was superior to T~35 DAS and D~0.50 kg a.i./ha (3.8 plants/m², 4.42 g/m² and 84.9%, respectively) over D~0.25 kg a.i./ha for the above-mentioned parameters (Table 5). The mean of BM (T₁ to T₈) treatments was on par to the standard herbicide atrazine + pendimethalin (C₁) 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 (T₆: S₂₅ T₂₅ D_{0.50}) and S~15 kg/ha + T~25 DAS + D~0.5 kg a.i./ha (T₂: S₁₅ T₂₅ 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

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 ≤ 0.05)	1.0	1.03	2.12
<i>Sesbania</i> seed rate (S)			
15 kg/ha	4.3	4.89	81.4
25 kg/ha	3.9	4.52	84.2
LSD (P ≤ 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 ≤ 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 ≤ 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 ≤ 0.05) _{Control}	0.3	0.28	2.41
^c LSD (P ≤ 0.05) _{C₁/C₂/C₃ v. BM}	0.3	0.30	2.53

BM, brown manuring treatment mean (T₁ to T₈).

^aSquare-root ($(x + 0.5)^{1/2}$) transformed values. For details of treatments, see Experiment II in Table 1.

^bLSD for pair-wise comparison among the controls (C₁, C₂, C₃).

^cLSD for pair-wise comparison between C₁/C₂/C₃ v. BM.

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).

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 (T₂: S₁₅ T₂₅ D_{0.50}). The later registered a 3-year mean grain

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 ≤ 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).

^bSquare-root $(x + 0.5)^{1/2}$ 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
<i>Sesbania</i> 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 ≤ 0.05)		0.2	0.22	0.11	24

^aSquare-root $(x + 0.5)^{1/2}$ transformed values.

^bSee 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 ≤ 0.05)		0.2	0.22

^aSquare-root $(x + 0.5)^{1/2}$ 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~0.50 kg a.i./ha (T₂: S₁₅ T₂₅ 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).

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 ($P \leq 0.05$)	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 ($P \leq 0.05$)	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 ($P \leq 0.05$)	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 ($P \leq 0.05$)	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 ($P \leq 0.05$) _{Control}	0.15	0.11	2.8
^b LSD ($P \leq 0.05$) _{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 (T₁ to T₉).

^aLSD for pair-wise comparison among the controls (C₁, C₂, C₃).

^bLSD 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/m²) compared to *Sesbania* populations (~45–60 plants/m² at 1.5 g seed/m²; 75–100 plants/m² at 2.5 g seed/m²). 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, T₆ (25 kg/ha *Sesbania* seed + 2,4-D 0.50 kg a.i./ha applied at 25 DAS) and T₂ (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 (T₉). 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

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 ($P \leq 0.05$)	–	NS	NS	NS
<i>Sesbania</i> seed rate (S)				
15 kg/ha	508	1325	817	1.61
25 kg/ha	514	1242	728	1.42
LSD ($P \leq 0.05$)	–	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 ($P \leq 0.05$)	–	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 ($P \leq 0.05$)	–	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 ($P \leq 0.05$) _{Control}	–	34	34	0.07
^c LSD ($P \leq 0.05$) _{C1/C2/C3 v. BM}	–	36	36	0.07

BM, brown manuring treatment mean (T_1 to T_6).

^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.

^bLSD for pair-wise comparison among the controls (C₁, C₂, C₃).

^cLSD 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

performance of T₂ 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.*, 2010a, 2010b), accumulating soil C and N (Sharma *et al.*, 2010a, 2010b), 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 T₂. However, the treatment T₆, 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 S₁₅ T₂₅ D_{0.50} (T₂) 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 T₂ was lower by \$92.0 (~15.3%) and NR higher by \$72.0 (~9.0%). Thus, the T₂ 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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