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Density-effect and economic threshold of purple nutsedge (*Cyperus rotundus*) in soybean

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Abstract Purple nutsedge (∼nutsedge) is an important perennial weed, which infests soybean in India and causes high yield losses. Selective pre-emergence herbicides hardly control nutsedge. Post-emergent application of imazethapyr is effective against nutsedge with almost 70 % efficiency. Information on the interference effect of nutsedge across densities on soybean and its economic threshold (ET) is hardly available, but would be useful for its management, and saving herbicide treatments with lower densities. An experiment was designed to evaluate the interference of nutsedge in pure stands, and that of natural weed infestations on soybean. Moreover, it was aimed to determine ET of nutsedge in soybean. The dry weights of weeds in the treatments 'natural weeds including nutsedge' and the one of nutsedges in the pure stand density of nutsedge 200 plants/m^2 were similar and higher than weed biomass in other nutsedge densities. The 'natural weed infestation both including and excluding nutsedge' and the treatment of 200 nutsedge plants/m^2 caused greater reductions in soybean yields and were the most competitive. The ET of nutsedge in soybean was 19–22 (∼mean 21) plants/m^2, considering 70 % efficiency of the herbicide imazethapyr. It predicts that a density of 21 nutsedge plants/m^2 can cause 9.1–11.5 % yield losses, which are an economic loss under this situation. This ET would help in making decisions for nutsedge management and fitting models and could be used for other similar sites with nutsedge dominance. This ET, considering several production factors, is more precise and reliable than the ET determined with only yield losses.

Keywords *Cyperus rotundus* · Economic threshold · Interference · Purple nutsedge · Soybean · Weed

Introduction

Soybean [*Glycine max* (L.) Merrill] is widely cultivated in Brazil, USA, Argentina, China, India, Paraguay, Canada, Ukraine, Bolivia, Uruguay and the Russian Federation (in order of decreasing level of production) (USDA 2013). In India, it ranks first among oilseed crops grown in terms of hectarage sown (10.8 million hectares) and annual production (11.5 million tonnes). Soybean (during rainy season)–wheat (during winter) is an important double-cropping system on the Vertisols of the semi-arid tropical region of India (Hazra et al. 2011). Having slow initial growth process up to 40–50 days after sowing (DAS), soybean is commonly infested with weeds, including purple nutsedge (*C. rotundus* L.; family *Cyperaceae*; hereafter referred to as nutsedge) (Kumar et al. 2012). After almost 15–20 years of cultivation of soybean using pre- and/or post-emergence selective herbicides, nutsedge has emerged as an important weed in soybean in several areas of central and northern India (Kumar et al. 2012) and causes considerable yield losses (Hazra et al. 2011). Dev et al. (1997)

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reported that 148 and 165 nutsedge shoots/m^2 caused a reduction in soybean yield by 29 and 36 %, respectively. Nelson and Smoot (2010) observed that yellow nutsedge (*Cyperus esculentus* L.) densities from 2.2 to 13 plants/m^2 in a high-yield year (2000), and 4.3–13 plants/m^2 in a low-yield year (2001) reduced soybean yields by 9–34 %.

Nutsedge, originated in Asian region (mainly, India), is distributed throughout the tropics and sub-tropics of the world (Holm et al. 1991) and interferes with 52 crops in 92 countries (Das 2008). It is a highly invasive weed with colonization habit (Rogers et al. 2008) and multiplies rapidly through extensive network of underground tubers, showing strong apical dominance (Nelson and Renner 2002; Edenfield et al. 2005; Webster et al. 2008). It is a perennial weed with consistently increasing growth up to the maturity of soybean and is highly persistent and difficult to be controlled by the usual selective pre- or post-emergence herbicides applied to soybean (Holm et al. 1991; Das 2001, 2008; Kumar et al. 2012). Nutsedge shows tolerance to these herbicides, mainly, because of the pre-emergence mode of application on the soil surface, which provides less or no contact of these herbicides with tubers lying deeper in soil. Most selective herbicides by means of controlling most annual grass and broad-leaved weeds (Vyas and Jain 2003) leave the soybean fields almost free from natural weed competitors to perennial weeds like nutsedge, which, then, thrive better with available growth resources. Thus, continuous use of these herbicides has led to the preponderance of nutsedge, which appears in almost pure stands in soybean. In most situations, hand weeding is adopted at 25–30 days after pre-emergence herbicide treatment to control nutsedge (Kumar et al. 2012). But, recently, post-emergence application of imazethapyr at 0.075–0.100 kg/ha has been found to be effective against nutsedge (Grichar and Sestak 2000; Kumar et al. 2012). Imazethapyr is a broad-spectrum herbicide and highly selective to soybean. A suitable intercrop or cover crop is hardly reported for soybean, as it is a short-stature crop and grown closely with a narrower row space. However, in situ *Sesbania aculeata* L. (*Dhaincha*) grown up to 25 DAS, and then uprooted and spread as mulch in between the rows of soybean has been found to be effective against nutsedge/weeds (Kumar et al. 2012). Soil solarization (Miles et al. 2002; Das and Yaduraju 2008) with a follow-up application of non-selective systemic herbicide glyphosate (Kumar et al.2012) can effectively control nutsedge. Glyphosate and glufosinate-AM (Das and Yaduraju 2002) can also be used in stale seed beds to control nutsedge/weeds before soybean is sown. Besides herbicide use, integrated weed management practices would include correct soil tillage to enhance tuber desiccation (Rambakudzibga 1999).

To be useful in practical decision, the economic threshold (ET) of weed should be calculated, which is the density at which the cost of control equals to the benefit obtained from controlling weed (Cussans et al. 1986; Cousens 1987). This parameter helps in deciding whether or not a treatment against a weed is necessary and economical (Hazra et al. 2011; Dodamani and Das 2013). The ET concept is the foundational doctrine of pest/weed population management, which rejects eradication of pest/weed in favour of regulation of their populations at economically optimum levels (Wilkerson et al. 2002). The ET has become the basis of most weed management decision models (Coble and Mortensen 1992; Thornton and Fawcett 1993; Wilkerson et al. 2002). The ET-based weed management using effective post-emergence herbicide like imazethapyr in soybean may help to rationalize herbicide use, leading to possible reduction in herbicide intake from the present levels by reducing doses (Swanton and Weise 1991; Thomas et al. 2011). The knowledge of the ET may also be useful for non-chemical nutsedge control methods.

The biology and ecology of nutsedge, and its seasonal variations in growth have been studied enough (Jordan-Molero and Stoller 1978; Keeley 1987). In tropical India, nutsedge grows luxuriantly during wet rainy season, but the growth is much reduced and suppressed during winter due to low temperatures (Das and Yaduraju 2008). In the context of global climate change, nutsedge is supposed to pose more interference on soybean or other crops due to its higher water-use efficiency, greater leaf area, root length and dry weight, and greater numbers of tubers and tillers in response to elevated CO_2 level (Rogers et al. 2008). The impact of nutsedge densities on soybean, and the minimum density, which can cause economic losses have never been investigated in India and little worldwide. The aim of this work was to find out the degree of interference of nutsedge across various densities in soybean, and to determine its ET.

Materials and methods

Experimental sites

The experiments were undertaken at the Indian Agricultural Research Institute, New Delhi during 2006–2009 (4 years) in a soybean field, which was infested with nutsedge. Soil was alluvium (Typic Ustochrepts; Order Inceptisol) in origin and sandy loam (62.4 % sand, 16.8 % silt and 19.2 % clay) with 0.54 % organic C and pH 7.7. The available P (17.5 kg P/ha) and K (180.1 kg K/ha) were medium, but available N (260.5 kg N/ha) was low in soil. In all the 4 years of experimentation, soybean was cultivated during the rainy season (July–October), and wheat during winter (November–March) and the site remained un-cropped fallow during the summer (April–June).

Table 1 Treatments adopted in the experiment

Nutsedge/weed infestation level	Treatment description	Treatment code
Nutsedge 0 plant/m^2 or weed-free check (WFC)	Free from all weeds including nutsedge through periodical manual weeding	Nut 0/WFC
Nutsedge 25 plants/m^2	No other weeds except nutsedge was present; first treated with pre-emergence pendimethalin 0.75 kg/ha at 2 days after sowing (DAS) of soybean to control weeds except nutsedge, and then hand pulling of other weeds and excess population of nutsedge for maintaining the required density of nutsedge from 20 DAS onwards	Nut 25
Nutsedge 50 plants/m^2	No other weeds except nutsedge was present; first treated with pre-emergence pendimethalin 0.75 kg/ha at 2 days after sowing (DAS) of soybean to control weeds except nutsedge, and then hand pulling of other weeds and excess population of nutsedge for maintaining the required density of nutsedge from 20 DAS onwards	Nut 50
Nutsedge 100 plants/m^2	No other weeds except nutsedge was present; first treated with pre-emergence pendimethalin 0.75 kg/ha at 2 days after sowing (DAS) of soybean to control weeds except nutsedge, and then hand pulling of other weeds and excess population of nutsedge for maintaining the required density of nutsedge from 20 DAS onwards	Nut 100
Nutsedge 150 plants/m^2	No other weeds except nutsedge was present; first treated with pre-emergence pendimethalin 0.75 kg/ha at 2 days after sowing (DAS) of soybean to control weeds except nutsedge, and then hand pulling of other weeds and excess population of nutsedge for maintaining the required density of nutsedge from 20 DAS onwards	Nut 150
Nutsedge 200 plants/m^2	No other weeds except nutsedge was present; first treated with pre-emergence pendimethalin 0.75 kg/ha at 2 days after sowing (DAS) of soybean to control weeds except nutsedge, and then hand pulling of other weeds and excess population of nutsedge for maintaining the required density of nutsedge from 20 DAS onwards	Nut 200
All weeds including nutsedge	Natural infestation of weeds including nutsedge; unweeded control (UWC); no application of pre-emergence pendimethalin	UWC
All weeds excluding nutsedge	Natural weed infestation excluding nutsedge (UWC-Nut); no application of pre-emergence pendimethalin	UWC-Nut

Treatments

The treatments were eight infestation levels of nutsedge or weeds, which included six pure stand densities of nutsedge (0, 25, 50, 100, 150 and 200 plants/m^2), and two natural weed infestations including nutsedge (UWC) and excluding nutsedge (UWC-Nut) (Table 1). The UWC and UWC-Nut were adopted to compare the interference potential of nutsedge in pure stand densities with that of the infestations of natural composite weeds with or without nutsedge. As the density-effect of nutsedge on soybean is hardly available in India or the neighbouring countries, the densities were chosen arbitrarily considering its lanceolate leaves, cylindrical and upright stems and overall growth/vigour in soybean fields. Treatments were laid out in a randomized complete block design with three replications. Pendimethalin was not a treatment, but a common application of pendimethalin 0.75 kg/ha at 2 DAS was made to all nutsedge densities plots to eliminate other weed species and achieving uniform pure stands of nutsedge. The required densities of nutsedge were maintained from 20 DAS by periodical counting, and hand pulling of its excess population, and of other weeds, escaping pendimethalin treatment (Table 2). Weed-free check (WFC) were kept free from weeds throughout the crop-growing period by manual weeding since 10 DAS. The gross and net (i.e. area actually harvested) plot sizes were 4.0 m by 2.8 m, and 3.0 m by 2.0 m, respectively.

Imazethapyr[2-{4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl}-5-ethyl-3-pyridinecarboxylic acid; Pursuit 10 EC®] is a broad-spectrum herbicide, highly selective to soybean and effective against nutsedges (Grichar and Sestak 2000; Das 2008). It was applied at 0.075 kg/ha 20 DAS with 350 l/ha of water using a knapsack sprayer fitted with a flat fan nozzle (Sukun Agencies India, Mumbai, Maharastra, India) to soybean grown in three extra plots for determining its nutsedge control efficiency (H), which was required for determining the ET of nutsedge in soybean.

Soybean variety and agronomic practices

Seeds of soybean ‘Pusa 20’ (Division of Genetics, Indian Agricultural Research Institute, New Delhi) were inoculated with *Bradyrhizobium japonicum* L. and were sown in the first week of July every year by a tractor-drawn seed drill with 60 kg seed/ha at 40.0 cm spacing between rows. The recommended dose of N (40 kg N/ha), P (60 kg P_2O_5/ha)

Table 2 Natural weed growth at 20 DAS of soybean under 'all weeds including nutsedge' (UWC), and in one of the nutsedge density plots treated with pendimethalin 0.75 kg/ha at 2 DAS

Botanical name of weed	Common name of weed	Weed growth in UWC		Weed growth after pendimethalin application in one nutsedge density plot[b]	
		Weed density (No/m^2)[a]	Weed dry weight (g/m^2)[a]	Weed density (No/m^2)[a]	Weed dry weight (g/m^2)[a]
Trianthema portulacastrum	Horse purslane	224 ± 5.3	102.5 ± 4.3	11 ± 2.5	7.5 ± 1.4
Cyperus rotundus	Purple nutsedge; Nutsedge; nutgrass	97 ± 3.4	18.5 ± 1.8	236 ± 11.5	78.3 ± 6.5
Acrachne racemosa	Goosegrass	65 ± 3.1	24.3 ± 1.6	6 ± 1.2	3.5 ± 0.8
Digera arvensis	Kanjero	34 ± 1.5	14.3 ± 0.9	17 ± 2.4	8.5 ± 1.3
Digitaria sanguinalis	Large crabgrass	13 ± 1.3	4.4 ± 0.6	0	0
Commelina benghalensis	Tropical spiderwort; wandering jew	12 ± 1.7	6.8 ± 0.3	3 ± 0.71	1.7 ± 0.5
Total		445	170.8	273	99.5

[a] Mean (± SD) weed data of six [three replications × 2 years (2006 and 2007)] quadrats (each of 0.5 × 0.5 m area)

[b] Pendimethalin was not a treatment, but applied to all nutsedge densities plots for controlling other weeds and making a uniform pure stand of nutsedge with the required densities

and K (40 kg K_2O/ha) in the form of urea, single superphosphate and muriate of potash, respectively, were applied uniformly to all plots as basal fertilization. Other practices (irrigation and pest management) as recommended were followed for raising soybean crop.

Plant sampling and observations

To assess weed infestation, a quadrat (0.5 m by 0.5 m) was randomly placed in each plot and all weeds were collected and sun-dried for 2 days. Afterwards, the samples were kept in an oven at 70 ± 5 °C for 48 h and their dry weight was recorded. At maturity, all soybean plants from the net plot of each plot/treatment was harvested and threshed. Then, seeds were separated and cleaned, and yield was recorded. The observed yield losses (%) across the treatments were calculated using Eq. 1 (Das 2008).

$$\text{Yield loss} = [(\text{Ywf} - \text{Yt}) * 100]/\text{Ywf} \quad (1)$$

where Y_{wf} and Y_t are soybean yields in weed-free check and treatment, respectively.

Simulation of soybean yield and yield loss

A rectangular non-linear hyperbolic regression model (Eq. 2) (Cousens 1985) was used to simulate soybean yields (Y) across the nutsedge densities (d).

$$\text{Y} = \text{Ywf}\ [\ 1 - \text{id}/100(1 + \text{id/A})] \quad (2)$$

where Y, simulated soybean yield at 'd' weed density; Ywf, weed-free crop yield; i, per cent yield loss per unit weed density (d) as $d \rightarrow 0$, and A, the asymptotic value of the maximum yield loss (%) as $d(density) \rightarrow \infty$.

An iterative method was used for fitting data to non-linear equations in the 'SPSS' package (Norris 1992) and the values of 'i' and 'A' were estimated. The data and fitted curves are presented in terms of per cent yield loss (Y_L) using Eq. 3.

$$\text{Y}_\text{L} = \text{id}/(1 + \text{id/A}) \quad (3)$$

where Y_L, yield loss (%); i, d and A are defined above.

Natural weed infestations UWC and UWC-Nut did not have a fixed density of nutsedge. Therefore, they were not considered for simulating the soybean yield (using Eq. 2) and yield losses (using Eq. 3) as well as for studying correlations between observed and simulated yields and yield losses, and for regression analysis between soybean yield and nutsedge density.

Determination of economic threshold of nutsedge

The ET of nutsedge (Cousens 1987) was determined using the following quadratic equation (Eq. 4).

$$1 + (\text{i/A})[2 - \text{H} - (\text{YPAH/C})]\ \text{T} + (\text{i/A})^2(1 - \text{H})\ \text{T}^2 = 0 \quad (4)$$

where 'i' and 'A' are defined above; Y, weed-free soybean seed yield; P, unit price of soybean seed (i.e. minimum support price of the Government of India); H, efficiency of herbicide imazethapyr; C, cost of nutsedge control (i.e. cost of imazethapyr and its application); T, economic threshold density.

Statistical analysis

The data on soybean and nutsedge/weeds were analyzed by the technique of analysis of variance (ANOVA) for a randomized complete block design using MSTAT C (CIMMYT, Mexico City, Mexico) software. Significance was tested by variance ratio (i.e. *F value*) at $P \leq 0.05$ (Gomez and Gomez 1984). Standard error of difference between means (SE) and least significant difference (LSD) were worked out for comparing the treatment means. Nutsedge/weeds dry weight and soybean yield of 4 years were subject to pool analysis to find out the variation of these two parameters across the years and the treatments as well as the year x treatment interactions, which were found significant at $P \leq 0.05$. Therefore, the mean data of nutsedge/weeds dry weight and soybean yield have been presented year-wise. Correlation coefficients between observed and simulated yields and yield losses were worked out for a logical conclusion of the simulated data. Regression analysis was performed to find out the relationship between nutsedge densities and soybean yield. Before analyzing regressions, the normality was tested by Sapiro–Wilk test using SAS software (SAS Institute, Cary, NC). It was found that the errors/residual yields across the densities of nutsedge followed normal distribution.

Results

Growth of nutsedge/weeds

The natural weed infestation in soybean (Table 2) composed of six weed species, namely, horse purslane (*Trianthema portulacastrum* L.), purple nutsedge/nutsedge/nutgrass (*C. rotundus* L.), goosegrass (*Acrachne racemosa* (Heyne ex Roem and Schult) Ohwi.), kanjero (*Digera arvensis* (L.) Forsk.), large crabgrass (*Digitaria sanguinalis* (L.) Scop.) and tropical spiderwort/wandering jew (*Commelina benghalensis* L.). Under unweeded situations (UWC), horse purslane was the most important weed followed by nutsedge, but nutsedge appeared as the most important weed when soybean was applied with pre-emergence pendimethalin at 0.75 kg/ha 2 DAS. In UWC, nutsedge had a density of 97 ± 3.4 plants/m^2, which accumulated a dry weight of 18.5 ± 1.8 g/m^2 (Table 2). But, after a treatment of pendimethalin 0.75 kg/ha 2 DAS, its density increased to 236 ± 11.5 plants/m^2 with a dry weight of 78.3 ± 6.5 g/m^2.

The pooled analysis revealed a significant variation in nutsedge/weeds dry weight across the years and the treatments (Fig. 1a, b, c, d). The mean dry weight of nutsedge/weeds was almost 1.5 times higher in the second year 2007

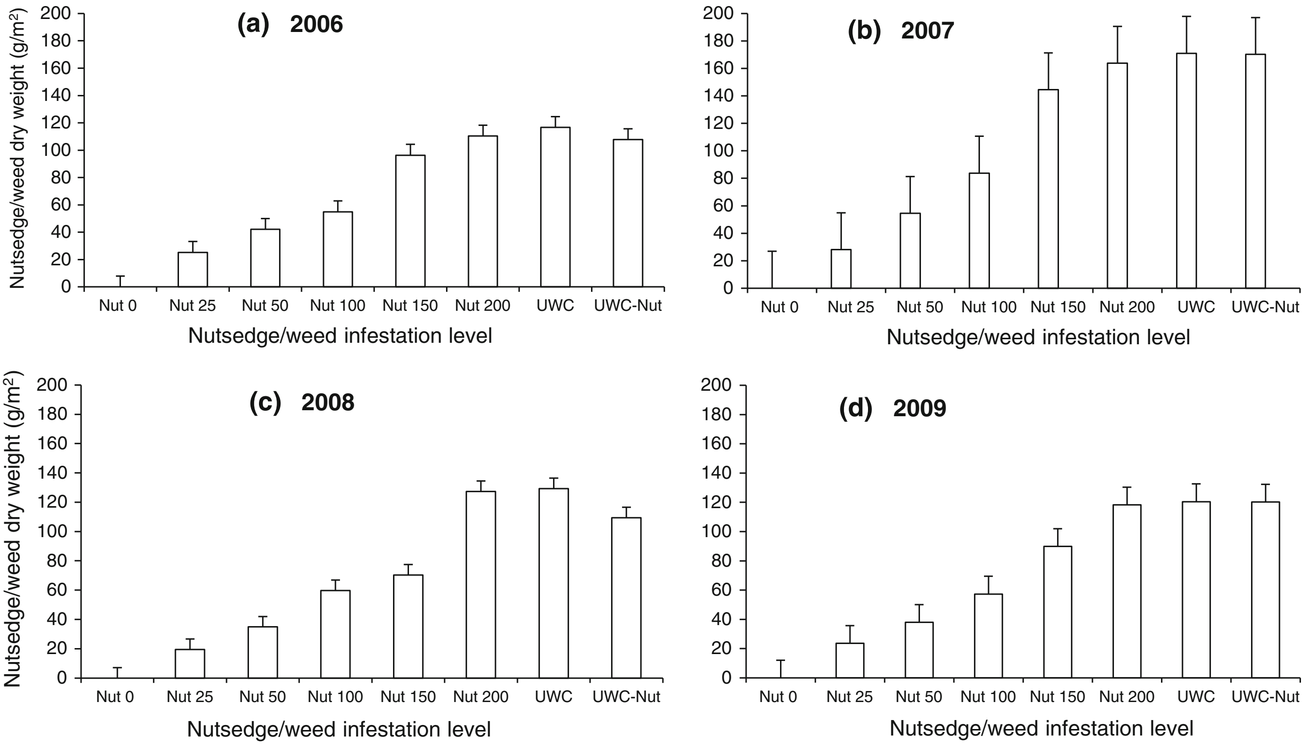

Fig. 1 Nutsedge/weed dry weight (g/m^2) in different nutsedge/weed infestation levels in 2006 (**a**), 2007 (**b**), 2008 (**c**) and 2009 (**d**); *Bars* indicate LSD at $P < 0.05$

compared to 2006, 2008 and 2009 in which the dry weights were similar. Therefore, the mean nutsedge/weeds dry weights of the treatments over replications in particular year have been presented. The nutsedge dry weight increased with increasing density in every year. At particular density, it was significantly higher than that at its lower densities and significantly lower than that at its higher densities all 4 years, except the year 2007, where Nut 150 and Nut 200 were similar in this regard. The dry weight accumulated by all natural weeds in UWC treatment and the dry weight of nutsedge plants recorded at Nut 200 were similar in all the years. These dry weights were significantly higher than those in all other nutsedge densities, except the Nut 150 in the year 2007. In this regard, ‘natural weeds excluding nutsedge’ (UWC-Nut) was similar with UWC and Nut 200 treatments in 2007 and 2009.

Soybean seed yield

Soybean seed yield differed significantly across the years and the treatments (Table 3). The year x treatment interaction was also significant. Increasing density of nutsedge from Nut 25 to Nut 200 caused an almost proportional decrease in yield in all the years as well as on the four-year mean yield. Compared to soybean yield in WFC, the yields were significantly lower in the ‘natural weed infestations’ (UWC), and ‘natural weed infestations excluding nutsedge’ (UWC-Nut) treatments, and in all the pure stand densities of nutsedge (i.e. Nut 25, 50, 100, 150 and 200) in all the years. The UWC resulted in the lowest yield, but Nut 200 and UWC-Nut were comparable with it in this regard (Table 3). The yields in other nutsedge densities (i.e. Nut 25, 50, 100 and 150) were intermediate, but significantly higher than that in UWC. The soybean yield and nutsedge density was inversely related, and there was a sharp decrease in yield as the density of nutsedge increased in all the years (Fig. 2). The soybean yield at almost every density of nutsedge was higher in 2009 and lower in 2008 compared to the yields obtained in 2006 and 2007.

Table 3 Soybean seed yield (t/ha) across the treatments and years

Treatment	Soybean seed yield (t/ha)			
	2006	2007	2008	2009
Nut 0 (WFC)	1.579	1.652	1.442	1.779
Nut 25	1.408	1.425	1.268	1.556
Nut 50	1.176	1.280	1.161	1.350
Nut 100	1.045	1.121	0.988	1.184
Nut 150	0.992	1.008	0.940	0.992
Nut 200	0.935	0.911	0.892	0.944
UWC	0.907	0.854	0.864	0.925
UWC-Nut	0.938	0.882	0.906	0.936
SE (d.f. 14)[a]	0.0119	0.0338	0.0236	0.0182
LSD ($P \leq 0.05$)	0.0361	0.1024	0.0715	0.0552

[a] Degrees of freedom

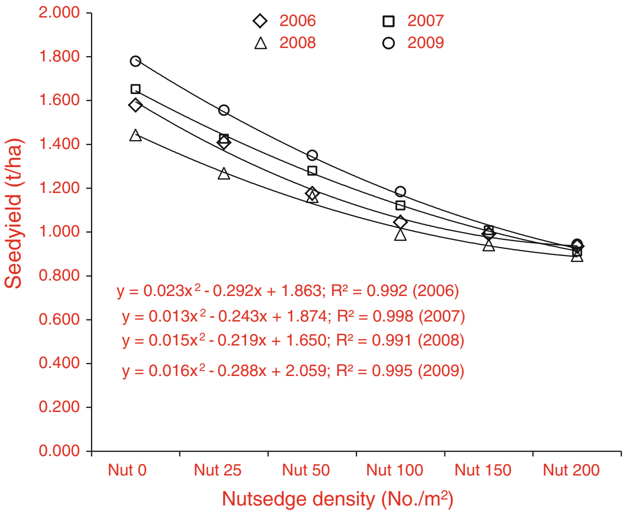

Fig. 2 Relationship between nutsedge densities and soybean seed yield (t/ha) across the years (2006, 2007, 2008 and 2009); The regression equation and R^2 value have been shown against each year

Simulation of yield and yield loss and economic threshold

In general, the simulated yields were higher than the respective observed yields (Table 4) at all the nutsedge densities, except at the Nut 25. Based on a residual of $\leq$0.15 t/ha yield, the observed and simulated yields were found to be comparable at every nutsedge density up to Nut 100 in 2006 and 2007, up to Nut 150 in 2008 and up to Nut 50 in 2009. The residual was wider (>0.15 t/ha) at higher densities of Nut 150 and Nut 200 in all the years except 2008. The simulated yield losses were lower than the respective observed yield losses at almost all the nutsedge densities in all 4 years (Fig. 3a, b, c, d). However, the observed and simulated yields and yield losses were better correlated ($r = 0.975$, 0.968, 0.976 and 0.960, respectively, in 2006, 2007, 2008 and 2009 for both yield and yield loss). In 2006, 2007, 2008 and 2009 (Table 5), the ET of nutsedge was 21.3, 22.2, 21.4 and 18.7 plants/m^2, respectively, and the regression equation for ET was: $0.000278T^2 - 0.040979T - 1.0 = 0$; $0.000295T^2 - 0.038561T - 1.0 = 0$; $0.000266T^2 - 0.041089T - 1.0 = 0$ and $0.000317T^2 - 0.047529T - 1.0 = 0$; respectively. These were on a good fit with R^2 values, 0.95, 0.94, 0.95 and 0.92, respectively, in 2006, 2007, 2008 and 2009.

Table 4 Simulated and residual (observed *minus* simulated) soybean yields (t/ha) across the densities of nutsedge over the years

Nutsedge density (plants/m^2)	2006		2007		2008		2009	
	Simulated yield^{ab} (t/ha)	Residual (t/ha)	Simulated yield^{ab} (t/ha)	Residual (t/ha)	Simulated yield^{ab} (t/ha)	Residual (t/ha)	Simulated yield^{ab} (t/ha)	Residual (t/ha)
Nut 0 (WFC)	1.579	0.000	1.652	0.000	1.442	0.000	1.779	0.000
Nut 25	1.355	0.053	1.425	0.000	1.262	0.006	1.592	−0.036
Nut 50	1.266	−0.090	1.337	−0.057	1.168	−0.007	1.478	−0.128
Nut 100	1.188	−0.143	1.261	−0.140	1.104	−0.116	1.417	−0.233
Nut 150	1.153	−0.161	1.226	−0.218	1.076	−0.136	1.391	−0.399
Nut 200	1.133	−0.198	1.207	−0.296	1.060	−0.168	1.376	−0.432

[a] Equations, $Y = 1.579[1 - \{d/100(1 + d/32.87)\}]$, $Y = 1.652[1 - \{0.98d/100(1 + 0.98d/31.25)\}]$, $Y = 1.442[1 - \{0.91d/100(1 + 0.91d/30.56)\}]$, and $Y = 1.779[1 - \{0.83d/100(1 + 0.83d/25.53)\}]$ were used for simulating soybean yields in 2006, 2007, 2008 and 2009, respectively

[b] The observed and simulated yields were better correlated at $r = 0.975$, 0.968, 0.976 and 0.960, respectively, in 2006, 2007, 2008 and 2009

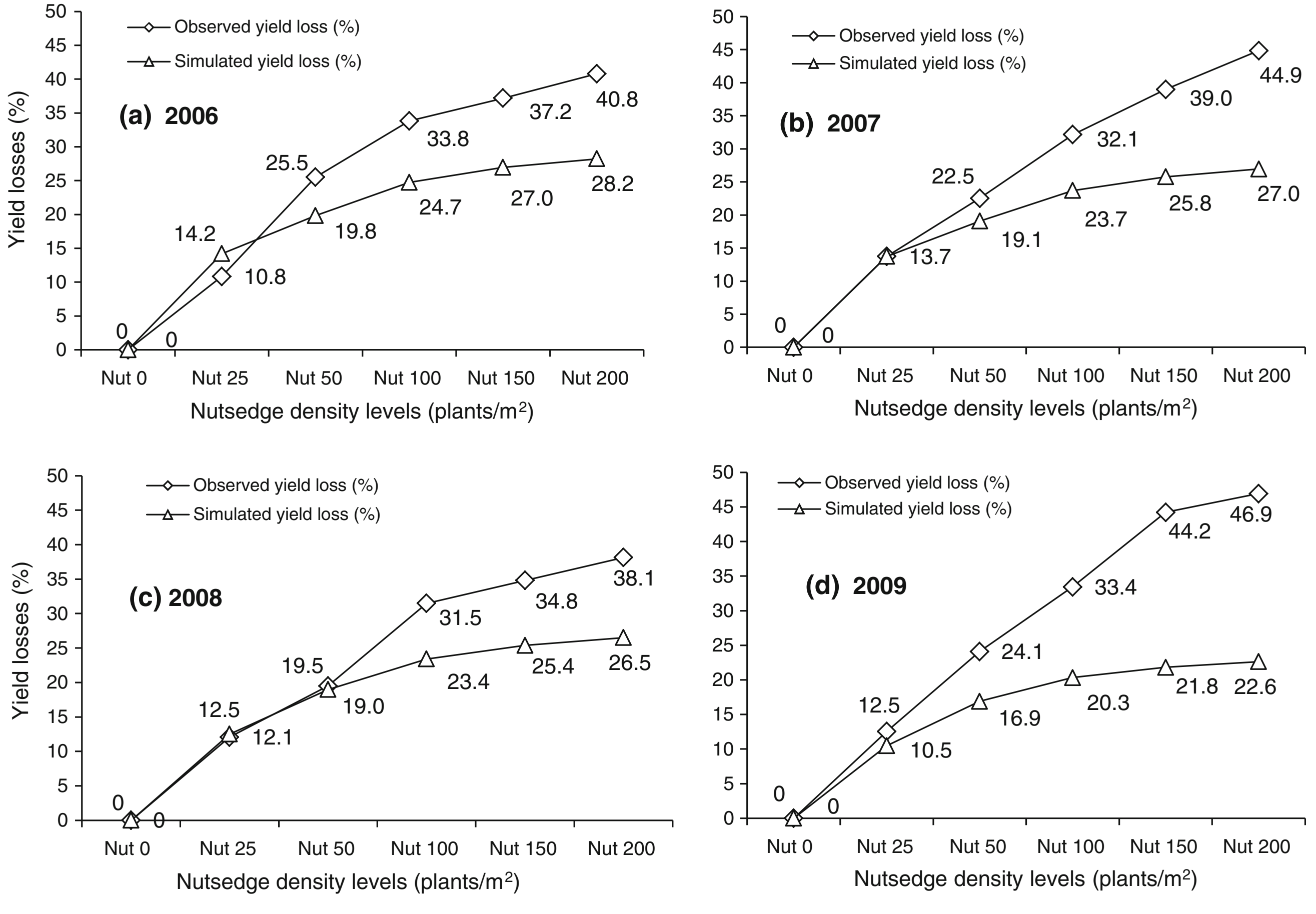

Fig. 3 Observed and simulated yield losses (%) of soybean across the densities of nutsedge in 2006(**a**), 2007 (**b**), 2008 (**c**) and 2009 (**d**); † Digital figures are the numerical values of yield losses

Discussion

Density-effect on nutsedge and weed interference

In the natural unweeded composite stands of weeds, nutsedge appears in good number (Table 2), but with less vigour and growth because its growth is usually suppressed due to luxuriant growth of annual grassy and broad-leaved weeds. Nutsedge is not a good competitor for light (Santos et al. 1997). Its canopy area is lower than that of many broad-leaved weeds, particularly horse purslane, which is the most dominant weed (Table 2) in soybean (authors'

Table 5 Economic threshold level of nutsedge (No/m^2) in soybean simulated through model across the years

Parameters	2006	2007	2008	2009
Y (Observed weed-free yield) (t/ha)	1.579	1.652	1.442	1.779
i (%)	1.0	0.98	0.91	0.83
A (%)	32.87	31.25	30.56	25.53
C (Cost of control by imazethapyr at 0.075 kg/ha) (INR/ha)[a]	1400	1500	1600	1600
H (Efficiency of imazethapyr) (%)	70	70	70	70
P (Price of soybean seed (INR/kg)[b]	10.2	10.5	13.9	13.9
Regression equation[c]	$[0.000278\ T^2 - 0.040979\ T - 1.0 = 0]$	$[0.000295\ T^2 - 0.038561\ T - 1.0 = 0]$	$[0.000266\ T^2 - 0.041089\ T -1.0 = 0]$	$[0.000317\ T^2 - 0.047529\ T - 1.0 = 0]$
Economic threshold level (T) (No/m^2)	21.3 (~21.0)	22.2 (~22.0)	21.4 (~21.0)	18.7 (~19.0)
R^2	0.95	0.94	0.95	0.92

[a] 1 US \$ = 54.30 INR or 1 INR = 0.0184 US \$ (approx.)

[b] Minimum support price for soybean declared by the Government of India in the respective years

[c] Derived from $[1 + i/A\{2 - H - (YPAH/C)\}T + (i/A)^2(1 - H)T^2 = 0]$ equation, using the values of parameters mentioned in this Table in the respective years

observation). In the absence of other weeds, nutsedge comes up virulently after soybean is treated with pre-emergence herbicides, killing most of the annual weeds.

Each tested nutsedge density resulted in a significant increase in dry weight of nutsedge over that in its lower densities, and a significant decrease in dry weight compared to that in its higher densities (Figs. 1a, b, c, d). The order of competitiveness based on four-year mean dry weight accumulated by weeds/nutsedge was: UWC > Nut 200 > UWC-Nut > Nut 150 > Nut 100 > Nut 50 > Nut 25. The density-effect of nutsedge on the reduction of soybean yield was significant from the lowest density of Nut 25, which increased with the increasing densities of nutsedge (Table 3). Similar negative effect of nutsedge densities or natural weeds was observed on the soybean leaf area, plant height and pods number/plant (data not shown). The UWC caused the greatest negative effect on soybean yield, but the UWC-Nut and the pure stand of nutsedge 200 plants/m^2 were comparable with it (Hazra et al. 2011; Dodamani and Das 2013). This indicates that these three nutsedge/weeds infestations were equally competitive to soybean. The order of negative effect of the treatments on four-year mean yield was: UWC = Nut 200 = UWC-Nut > Nut 150 > Nut 100 > Nut 50 > Nut 25. The UWC had a very high mixed weed population (445 plants/m^2 including 97 nutsedge plants), but its negative impact on soybean yield was not significantly higher from that of the Nut 200 and UWC-Nut. In UWC, probably, greater inter-specific competitions between weed species due to a greater density, and the varying competitive ability of weed species caused a reduction in the overall interference on soybean (Cousens 1985, 1987; Zimdahl 2004). The annual grassy and broad-leaved weeds growing for a short period do experience intra- and/or inter-specific competition due to usual over-crowding and mutual shading of canopies (authors' visual observation). In contrast, nutsedge has a underground network of tubers, which results in more uniform distribution of nutsedge plants over soil, reducing their aboveground intra-specific competition. Nutsedge plants might have experienced a lower or no intra-specific competition due to a medium pure stand density of nutsedge 200 plants/m^2. As a result, their cumulative interference in Nut 200 was slightly lower than, but comparable with that of the UWC. This corroborates the fact that a moderate weed infestation is sometimes as serious as heavy infestation (Das 2008). In the tropical Indian conditions during warmer months (April–September), nutsedge remains in various stages of growth based on the time of emergence and grows luxuriantly, mainly after the onset of monsoon rains in July. It's plants continue to grow green even when other weeds and soybean reached to maturity (authors' visual observation). This consistent growth habit helps nutsedge to compete with soybean for a longer period, up to the maturity of soybean.

Simulation of yield and yield loss and economic threshold

In this study, the observed yields (Table 3) were lower than the respective simulated ones (using Eq. 2; Table 4) due to which the observed yield losses were higher than the respective simulated ones (using Eq. 3; Fig. 3a, b, c, d) in almost all the nutsedge densities. The observed yields were affected more due to variation in growth of nutsedge and soybean across the treatments as well as across the years in response to prevailing climate and growth conditions (Santos et al. 1997; Hazra et al. 2011; Dodamani and Das 2013). The observed and simulated yields in weed-free check (WFC) being the same (Table 4), the observed yield losses (using Eq. 1) were higher than the respective simulated ones, and the difference between them was wider, particularly at Nut 100 and higher nutsedge densities. The values of 'i' and 'A' determined through iterative methods (Norris 1992) also influenced the simulated yield and yield loss. The model output, thus, was influenced slightly. The model, we used is widely applicable (Cousens 1985) and is based on weed density, which can easily be counted by the farmers. The simulation was frequently better at lower densities, and the observed and simulated yields and yield losses were better correlated ($r = 0.975$, 0.968, 0.976 and 0.960, respectively, in 2006, 2007, 2008 and 2009), probably, due to narrower differences ($\leq$0.15 t/ha) between the observed and simulated yields at lower nutsedge densities upto Nut 50 in 2009, upto Nut 100 in 2006 and 2007, and upto Nut 150 in 2008.

To ascertain the need of a weed control measure, the impact of weed interference on a crop should be predicted earlier (Hazra et al. 2011). The ET provides that baseline information for making weed control decisions (Cousens 1987) and plays an important role in setting up an integrated weed management programme (Coble and Mortensen 1992; Wilkerson et al. 2002). We observed that the ET of nutsedge varied from 19 to 22 plants/m^2 across the years (Table 5), which is lower than the 50 tubers/m^2 found by Keeley (1987). The variations in growth/vigour of crop and weed, cost of control, products price, and herbicide efficiency across sites and times are responsible for this variation in ET (Cheema and Akhtar 2006; Hazra et al. 2011; Dodamani and Das 2013). In this study, higher nutsedge interference, causing higher reduction in soybean yield; higher soybean price; higher efficiency of herbicide imazethapyr, incurring lower cost of control (Table 5) have reduced the ET level of nutsedge compared to that observed by Keeley (1987). Having slow initial growth up to 40–50 DAS (Kumar et al. 2012), soybean is commonly infested by weeds/nutsedge. In the experimental field, nutsedge is naturalized over time and appears early from 15 to 20 DAS with high population and grows consistently up to the maturity of soybean. The application of pre-emergence herbicides for long time, killing natural competitor annual weeds helped this weed to proliferate more in soybean. Higher growth and vigour of nutsedge might be responsible for higher soybean yield losses in this study. In addition to this, possible allelopathic effect of nutsedge on soybean was not studied but cannot be ruled out. Dev et al. (1997) observed similar yield reduction (29 and 36 %, respectively, at 148 and 165 nutsedge shoots/m^2). Nelson and Smoot (2010) reported 9 to 34 % yield reduction due to yellow nutsedge densities from 2.2 to 13 plants/m^2.

This ET takes several factors of crop production into account and is determined for 4 years and can be used for long-term weed management (Norris 1992) as it would be more precise and reliable (Dodamani and Das 2013) than the ET, which is determined on the basis of only yield loss. Besides, ET-based weed management can provide certain benefits like reduction in future weed populations and herbicide use, which are not considered in the overall merit of ET (Norris 1992). These benefits are difficult to be quantified, but their inclusion may make ET more useful.

The four-year mean ET of nutsedge (Table 5) was 20.7 ($\sim$21) plants/m^2. Considering 10.8–13.7 % yield loss due to Nut 25 across the years (Figs. 3a, b, c, d), the yield loss will be 9.1–11.5 % at nutsedge 21 plants/m^2. A lower density than Nut 25 was not adopted in this study, but the ET determined from the tested densities of nutsedge could predict that a density of nutsedge 21 plants/m^2 can cause an economic loss ($\sim$10 %) to soybean under this situation. Probable reasons have already been discussed. In the present situation, it is almost impossible to achieve such low nutsedge densities in the study area due to agronomic practices. Therefore, integrated weed management strategies must urgently be adopted to avoid yield losses. A different crop rotation and specific soil tillage may contribute to reduce the nutsedge problem.

Our results show that the 'natural weeds infestation with nutsedge' and a pure stand density of nutsedge 200 plants/m^2 accumulated dry weight of weeds/nutsedge comparable between them, but significantly higher than the dry weights recorded in other nutsedge densities. The 'natural weeds with and without nutsedge' and all the pure stand densities of nutsedge tested caused a significant reduction in soybean yield, but the 'natural weeds with and without nutsedge' and the density of nutsedge 200 plants/m^2 caused greater reductions in yield. The simulation of yield and yield losses using the yield density model was better at lower densities than at higher densities like nutsedge 150 and 200 plants/m^2. The ET of nutsedge in soybean was 19–22 plants/m^2, considering a post-emergent treatment of imazethapyr with 70 % efficiency. This ET is more precise and reliable and would be useful for making nutsedge control decision and fitting models. The ET-based control would lead to reduction in future nutsedge populations by preventing tuber build-up in soil, and herbicide intake through reduction in doses.

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