International Journal of Chemical Studies

P-ISSN: 2349–8528
E-ISSN: 2321–4902
IJCS 2019; 7(1): 1319-1334
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Received: 21-11-2018
Accepted: 25-12-2018

Vivek
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

RK Naresh
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

SK Tomar
K.V.K. Belipar, Gorakhpur, Narendra Dev University of Agriculture & Technology, Kumarganj, Faizabad, Uttar Pradesh, India

Sudhir Kumar
Division of Plant Physiology, Indian Agriculture Research Institute, New Delhi, India

NC Mahajan
Institute of Agricultural Science, Department of Agronomy, Banaras Hindu University, Varanasi, Uttar Pradesh, India

Shivani
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Correspondence
Vivek
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Weed and water management strategies on the adaptive capacity of rice-wheat system to alleviate weed and moisture stresses in conservation agriculture: A review

Vivek, RK Naresh, SK Tomar, Sudhir Kumar, NC Mahajan and Shivani

Abstract
Weeds are the major deterrent to the development of sustainable crop production. Since weeds dictate most of the crop production practices and causes enormous losses (37 per cent) due to their interference. Farmers follow several practices for managing weeds in different crops/cropping systems, of which at present the use of herbicides are on the top due to the scarcity of labours. While globally, agriculture accounts for 80–90% of all freshwater used by humans, and most of that is in crop production. In many areas, this water use is unsustainable; water supplies are also under pressure from other users and are being affected by climate change. Much effort is being made to reduce water use by crops and produce ‘more crop per drop’. There is substantial potential for further improvements owing to the progress in understanding the physiological responses of plants and control weeds to water supply, and there is considerable promise within the modern approaches, if linked to the appropriate environmental physiology. In other words weeds pose a major threat to world agriculture by reducing detrimentally crop yield and quality. However, at the same time, weeds are major interacting components of the agro-ecosystems. Abundance and diversity of weeds vary significantly among the several communities. In order to evaluate each community’s structure and the interactions among them, several population indices are used as key tools. The sustainability of these systems is being questioned because of environmental and economic concerns caused by global competition, production cost, soil degradation, environmental pollution, and concern over the quality of life. In recent years, an increasing number of herbicide resistant weeds and invasive alien plants have become prevalent and challenging to manage in India as elsewhere in the world. At present, 30 weed species have evolved resistance to herbicide that includes 48 commonly used herbicides. Although tactics such as crop rotation and biological control have been used to manage some weeds in India, weed control has and continues to rely primarily on herbicides. Research priorities for weed management include developing and implementing a preventive risk assessment framework and a better understanding of the mechanisms that allow some alien weeds to be highly aggressive and difficult to manage. Moreover, the development and evaluation of additional weed management tactics such as straw mulching, optimizing water management, and site-specific fertilizer and herbicide applications warrant further study.
The goal of this review is to facilitate the strategies on the adaptive to alleviate weed and moisture stresses of ecologically based alternative methods for weed management that will support rice-wheat system, which require less tillage, herbicide and other inputs. To accomplish this goal, research efforts must be radically expanded in crop ecology and in the development of ecologically based technologies for weed management. Adoption of conservation agricultural practices reduces the intensity of soil manipulation thereby creates an unfavourable condition for weed seed germination, reduces the organic matter depletion and soil d degradation. Thus, the sustainable approaches could be an option for alleviate weed and moisture stresses which leads to sustainable crop production.

Keywords: Ecological weed management, water productivity, weed dynamics, herbicide residues

Introduction
India is located to the north of the equator between 8°4' and 37°6' N latitudes-and between 68°1' and 97°25' E longitudes. She is the seventh largest country in the world and the second largest in Asia, with a land area of about 15,200 km and a coastline of 7,516 km. India measures 3,214 km from north to south and 2,933 km from east 'to west. Agriculture continues to be the backbone of the Indian economy as it employs 54.6% of the total work force. The total share of agriculture and its allied sectors to the gross domestic product was 13.9% in 2013-14.

Out of India's total cropped area of 192 million ha, less than one-half is under irrigation. The Indian agricultural production system has: a challenge to feed l7.5% of the global population with only 2.4% of land and 4% of the available water resources at its disposal. North-western IGP has played a vital role in the food security of India by contributing about 40% of wheat and 30% of rice to the central grain stock every year during the last four decades (Hira and Khera 2000). Cultivation of rice and wheat in a system mode for last five decades, however, led to a number of problems, threatening sustainability of the system. These are: (i) overexploitation of groundwater (Humphreys *et al*. 2010); (ii) development of herbicide resistance (Hobbs *et al*., 1997); (iii) formation of sub-soil hard pan with a consequent increase in bulk density; (vi) sharp decline in soil organic matter (Naresh *et al*., 2017) [31]; and (v) multi-nutrient deficiencies (Dwivedi *et al*., 2012). To counteract some of these problems, conservation agriculture (CA) is now being promoted which involves minimum soil disturbance, providing a soil cover through crop residues or other cover crops and crop rotations for achieving higher productivity (Jat *et al*., 2016).

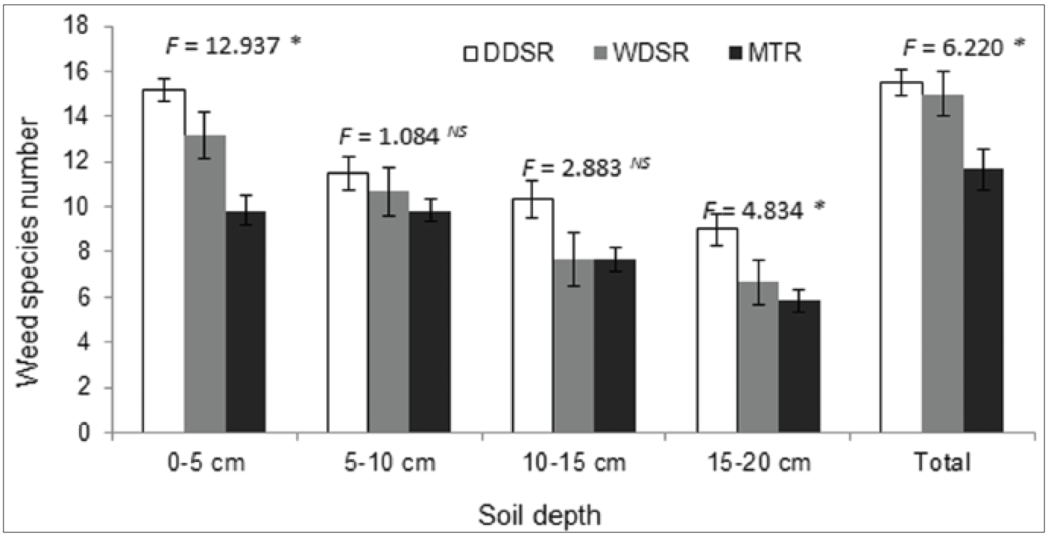
Farmers in this region mainly adopt transplanted rice owing to apparent advantages of puddling like less weed density, better soil chemical environment and nutrient availability in these mildly alkaline soils due to creation of an anaerobic condition. However, due to deterioration of soil physical health, zero-till direct seeded rice (DSR) is an alternative technology along with zero-till wheat (ZTW). Nonetheless, because of weed and residue management problems along with possible reduction in rice productivity in the initial years, farmers do not readily opt for zero-till DSR. On the other hand, a tilled DSR could be a novel technology in this region that avoids puddling, reduces weed problem and uses less water compared with puddling. Although studies in the past compared puddled transplanted rice-conventional-till wheat (TPR-CTW) versus zero-till DSR-ZTW, limited information is available on weed and water management strategies on the adaptive capacity of the tilled DSR-ZTW with or without rice residues compared with TPR-CTW in the region. Limited information is also available on impacts of CA practices (like brown manuring with Sesbania or green manuring with zero-till mung-bean with or without rice residue retention) on l weed and water management strategies on the adaptive capacity that are perceived to be most affected by tillage and residue management practices even within short period.

Recurrent moisture stress because of depleted water table, erratic rainfall and low water holding capacity of the soil, heavy weed infestation and soil degradation are among the major threats to irrigated agriculture widely practiced on undulated topography in the North Western IGP (NWIGP) of India. In addition, intensive tillage and low biomass input exacerbate the vulnerability of soil to erosion (Choudhury *et al*., 2016) [13] and soil organic carbon (SOC) reserves (Das *et al*., 2014) [15]. Furthermore, imbalance input agriculture (Ghosh *et al*., 2015) [21], the rapid growth of population (Das *et al*., 2015a) [17], and declining size of the holdings are additional constraints on marginal cultivated lands to feed the burgeoning population (Yadav *et al*., 2015; Naresh *et al*., 2018) [44, 32]. The low crop productivity because of moisture stress and heavy weed infestation aggravate food and nutritional insecurity of the region (Das *et al*., 2015b) [16]. Therefore, alternative management practices are required to conserve soil moisture and suppress weeds for enhancing the agronomic productivity of the NWIGP of India. Favourable climatic conditions (e.g., high humidity, temperature, soil moisture) in the NWIGP of India also enhance the growth of hardy weed species, which aggravates stress on crops by competing for limited resources and drastically reducing crop yield (Choudhury *et al*., 2016) [13]. Therefore, rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system of the NWIGP is prone to moisture stress and heavy weed infestation reducing agronomic yield and jeopardizing food security. Hence, this review study aimed all available information on weed and water management strategies on the adaptive capacity of rice-wheat system to alleviate weed and moisture stresses in conservation agriculture synthesized.

In conservation agriculture (CA) system, crop residues are left behind-on-the soil-surface. In- addition to moisture and soil conservation, the residues act as mulch and suppress weed seedling emergence (Chauhan, 2012) [8]. Inclusion of a cover crop between two main crops also helps reduce weed density in CA cropping system. In this, the cover crop can be killed by using a non-selective herbicide and its dead mulch be used to suppress weed germination by releasing allele-chemicals and/or reducing light transmittance to soil surface. Growing *sesbania rostrata* as a cover crop was found to control most of the weeds, leaving the field almost weed-free in rice-wheat cropping systems (Mahapatra *et al*., 2004) [25]. Similarly, mungbean can be grown as a cover crop in rice-wheat cropping system. Crop residues on the soil surface, as mulch, can influence germination and emergence of many weeds by altering the physical and chemical environments surrounding the seeds. The environmental factors include lower soil temperatures, shading, physical obstruction provided by mulch itself, allelopathy and toxic microbial products. The impact of crop residues on weed emergence, however, depends on the quantity and allelopathic potential of the residue and the weed species. The spreading of mulch on the soil surface reduces evaporation, saves water, protects from wind and water erosion, and suppresses weed growth (Singh *et al*., 2007) [38]. Mulching + dryland weeder at 20 DAS proved more effective in dry-seeded rice grown without herbicide use (Hussain and Gogoi, 1996) [24].

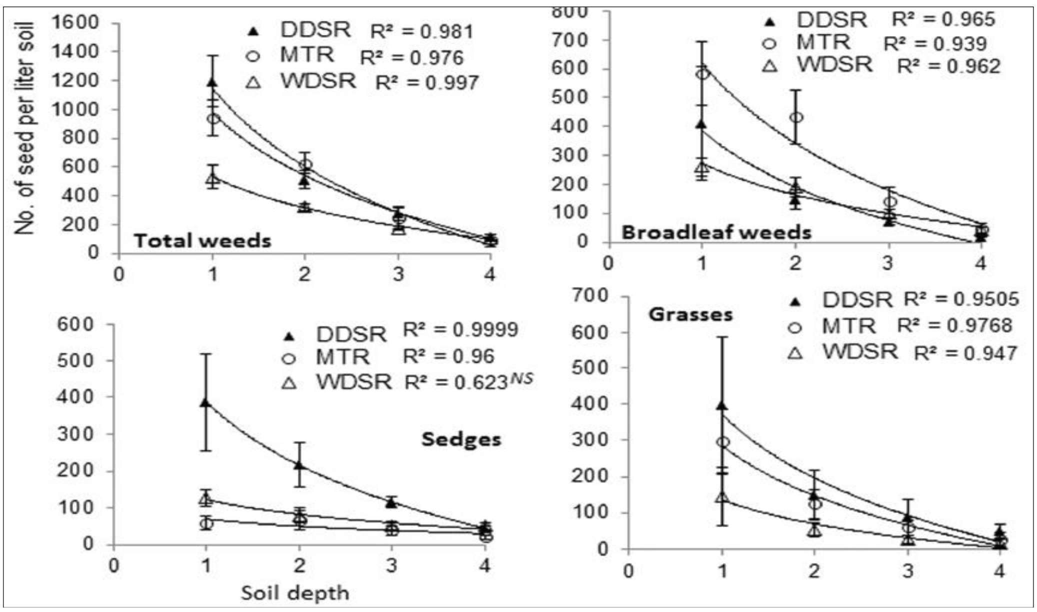
In India, a mulch of previous wheat crop residue at $4tha^{-1}$ reduced annual and broadleaved weed densities in dry-seeded rice compared with no mulch (Singh *et al*., 2007) [38]. Addition of crop residues can reduce seedling emergence of several weed species, but the quantities required to cause a substantial reduction in weed densities may be greater than those normally found in fields after harvest. Seed-drills, such as the Turbo Happy seeder and rotary-disc, are capable of seeding into loose residue of up to $6tha^{-1}$. It will be important, however, to balance the quantity of residue required to suppress weeds with quantities that will not hinder rice emergence in direct-seeded systems. Devasinghe *et al*. (2011) [19] observed that the application of rice straw mulch at the rate of $4tha^{-1}$ was effective in weed management under direct wet seeded rice method. Rice straw can stay long in the field due to higher lignin and silica contents as well as low protein and digestibility (Hanafi *et al*., 2012) [23]. The new approaches of using rice straw for controlling weeds in different crops, indicated that rice straw can be used for mulching, which benefits in preventing weed growth as well as supplies organic matter for N-fixation by heterotrophic N-fixing microorganisms. Thus, use of rice straw as fertilizer as well as suppressing the weed growth due to its allelopathic potential can be a good approach to reduce the herbicide load. Singh and Guru, (2011) [37] observed that weed population and weed dry matter was lower at all the doses ($100gm^{-2}$, $200gm^{-2}$) of rice straw incorporated with the lowest in $500gm^{-2}$ rice straw treatment. Grain yield was also higher at all the doses of rice straw incorporation while it was lowest (2658 $kgha^{-1}$) in the weedy treatment. Highest grain yield (3,925$kgha^{-1}$) was obtained, irrespective of cultivars, in the treatment with the highest rice straw incorporation (500gm^{-1}). A total of 17 compounds were recorded in the straw. Among these, four compounds could be identified after comparing with phenolic standards. These were gallic acid, p hydroxy benzoic acid, ferulic acid and vanillic acid. Crop residue may be a good option for weed control as well improvement of soil health, however, availability and application of crop residue manually will be a major constraint in large area. Herbicides play an important part in managing weeds in CA. However, due to presence of crop residues on the soil surface, pre-emergence herbicides may not be very effective. Residues are known to intercept up to 80% of the applied pre-emergence herbicides. Therefore, there is a need to better understand the efficacy of different pre-emergence herbicides when applied in different crops in India. Because of the efficacy issue of pre-emergence herbicides, timing of post-emergence herbicides is critical in CA. Herbicide rotations and mixtures may improve the weed control spectrum.

Chen *et al*. (2017) [10] observed that the species richness of the weed seed-bank was significantly lower in MTR than in DDSR and WDSR fields [Fig.1a]. On average, seed-banks of 15.5, 15.0, and 11.7 weed species were observed in each DDSR, WDSR, and MTR field, respectively. Moreover, the weed seed-banks in DDSR showed the highest species richness among the three rice planting systems in each soil layer, in particular at a depth of 0 to 5 cm [Fig.1a]. However, with increasing soil depth, all different weed groups showed a significant decrease in seed abundance under different rice planting systems, except for sedges under WDSR, and the decreasing slopes of DDSR were all sharper than those of WDSR and MTR [Fig.1b]. Most seeds were distributed in soil at a depth of 0 to 10 cm, including 81.7% in DDSR, 82.5% in MTR, and 75.3% in WDSR.



(a)

Fig 1(a): Number of rice's companion weed species observed in soil samples with different soil depths of different fields with different rice planting systems. DDSR: dry direct-seeded rice, WDSR: Water direct-seeded rice and MTR: machine-transplanted rice [Source: Chen *et al*., 2017] [10].



(b)

Fig 1(b): Number of seeds per m2 soil for different weed groups within different soil depths (1 = 0–5 cm, 2 = 5–10 cm, 3 = 10–15 cm, and 4 = 15–20 cm) [Source: Chen *et al*., 2017] [10].

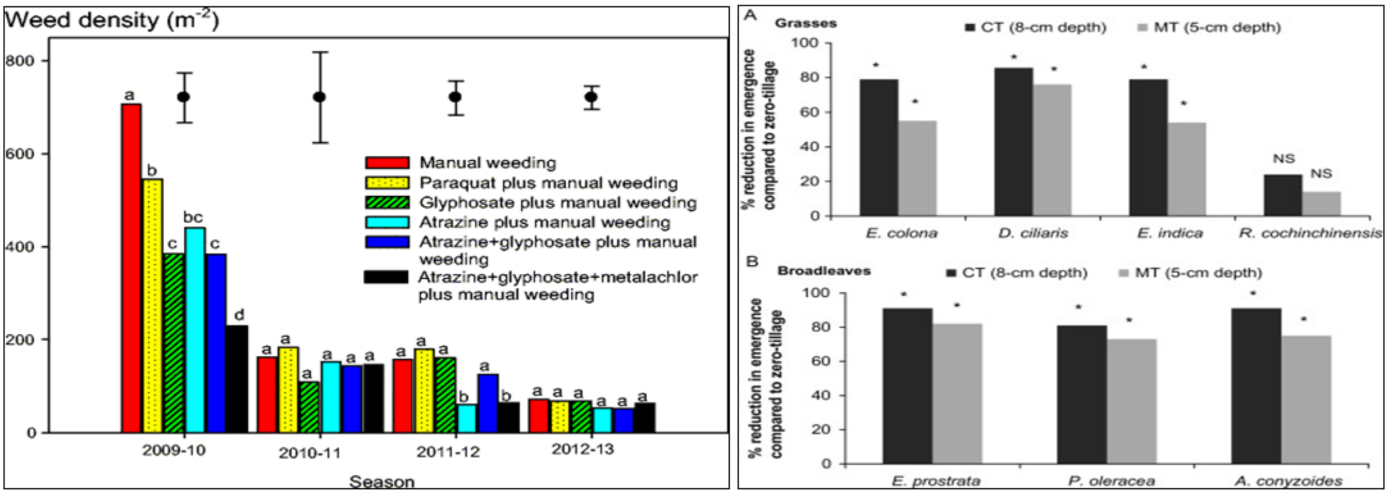


Fig 2(a): Impacts of six weed control strategies: manual weeding, paraquat plus manual weeding, glyphosate plus manual weeding, atrazine plus manual weeding, atrazine + glyphosate + manual weeding, and atrazine + glyphosate + metolachlor plus manual weeding on weed density (in m^{-2}) [Muoni *et al*., 2014] [29].

Muoni *et al*. (2014) [29] found that effective weed control including herbicides can gradually reduce weed pressure over the course of several years [Fig.2a]. This implies that, in the absence of adequate labor, intensive herbicide use would be necessary during the first 3 or 4 years. Thereafter, weeds could be more effectively controlled using mechanical or cultural methods. The authors also noted that combinations of contact and residual herbicides, such as atrazine, tended to be more effective against annual grasses and broadleaf species than paraquat or glyphosate alone. However, residual herbicides can only be used on specific crops and its use must be carefully considered (Ibid.). Factors such as weed density, dominant species, and farmer knowledge would need to be considered when establishing an herbicide application program. Chauhan *et al*. (2012) [9] additionally suggest using cover crops to support herbicide application; by using a non-selective herbicide such as glyphosate, the cover crop is killed and used as mulch, thereby limiting weed germination and growth.

Chamara *et al*. (2018) [7] reported that rice plants reached maximum emergence 9–13 days later under flooding compared with saturated conditions. Crop emergence decreased by 12–22% at 0.5 and 1 cm SD and by 48–60% at 2 cm SD, when combined with 2 or 5 cm FD compared with saturated conditions. Initial growth in rice plant height was slow under flooding but increased progressively after the seedlings emerged from water and the final height was not affected by FD [Fig.3a].

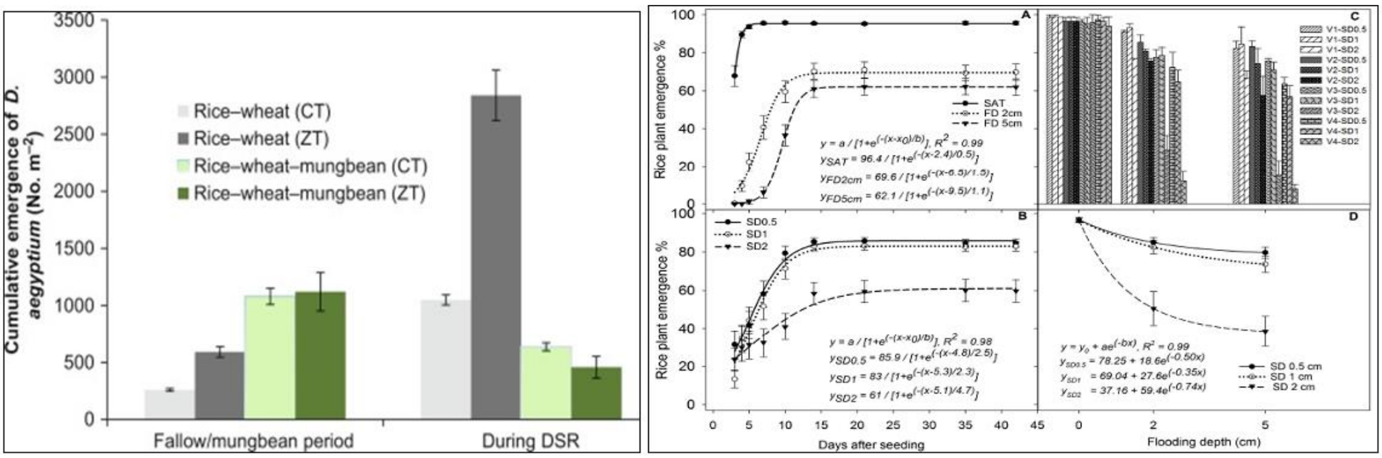


Fig 3(a): Percentage seedling emergence (A) under different flooding depths irrespective of sowing depth and genotype, (B) at different sowing depths irrespective of flooding depth and genotype, (C) of four genotypes under different sowing and flooding depths at 35 DAS, and (D) under different sowing and flooding depths at 35 DAS irrespective of genotype. [Source: Chamara *et al*., 2018] [7].

Chhokar *et al*. (2007) [12] reported that *Rumex dentatus* was significantly higher (12.1 plants/m^2) under zero tillage (ZT) compared to conventional tillage (CT) (1.9 plants/m^2). CT favoured *Phalaris minor*. The average P. minor dry weight under ZT and CT was 234.7 and 386.5 g/m^2, respectively. This differential response reflected was due to variation in seed distribution during puddling performed for rice transplanting [Fig.4b]. Metsulfuron and clodinafop were effective against broad-leaved and grassy weeds, respectively, whereas, sulfosulfuron besides controlling grassy weeds also controlled many broad-leaved weeds (Chhokar and Malik, 2002) [11]. About 80% of the interactions that has been observed in species of the family Poaceae (grasses) refer to cases of antagonism (Zhang *et al*., 1995) [45]. Whereas compatibility has been found to occur more frequently in mixtures where the companion herbicides belong to the same chemical groups (Damalas, 2004) [14]. Sulfosulfuron+ metsulfuron are compatible but tank mix application of clodinafop with either 2, 4-D or metsulfuron is antagonistic (Mathiassen and Kudsk, 1998) [27] and needs sequential application. The lower density of *R. dentatus* seeds led to its concentration in upper soil layer particularly on the surface, under ZT. Of the total seed found in upper 12.5 cm soil layer on the soil surface, about 0.02% and 1.24% was of *P. minor* and *R. dentatus*, respectively [Fig.4c]. Among the three tillage crop establishment methods, ZT and CT drill provided about 0.3 t/ha higher wheat grain yield over farmer's practice of CT-broadcast sowing [Fig.4a]. Continuous ZT adoption will help in reducing the more problematic weed *P. minor* but will increase the population of *R. dentatus*. However, *Rumex* spp. can be easily controlled with metsulfuron, chlorsulfuron, 2, 4-D or carfentrazone in wheat (Singh *et al*., 2004) [36].

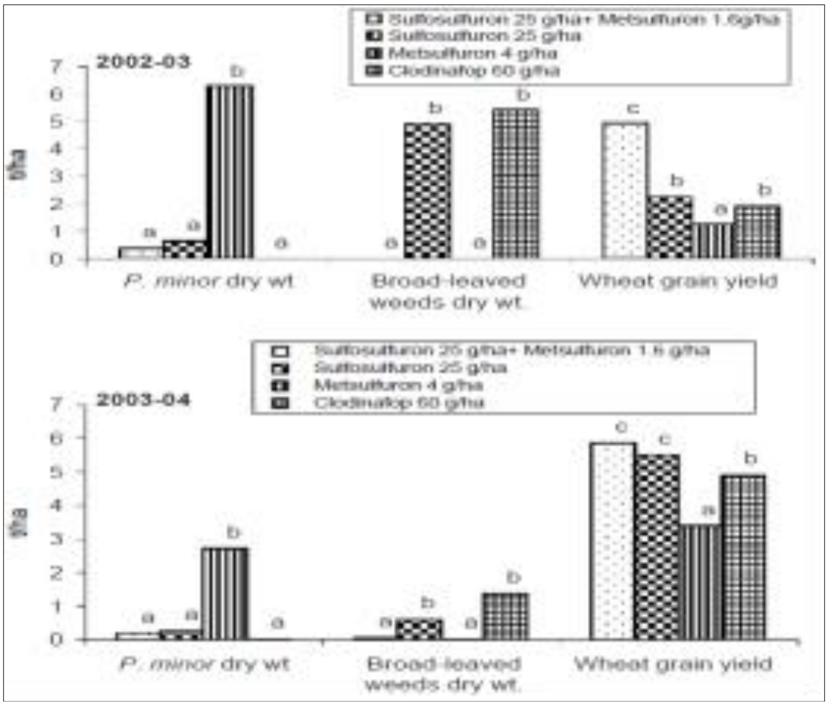
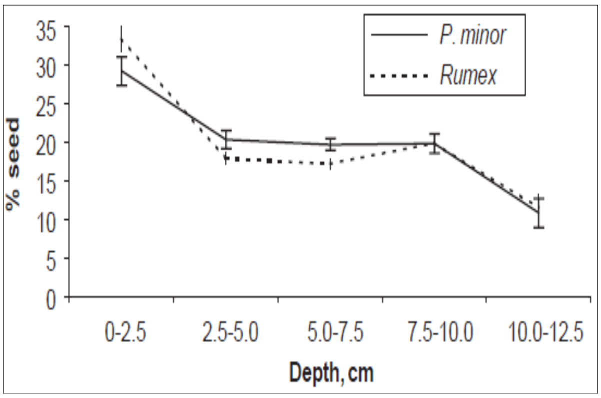


Fig 4(a): Effect of herbicides on weeds (*P. minor* and broad-leaved) and wheat productivity in ZT during 2002–2003 and 2003–2004 [Source: Chhokar *et al*., 2007] [12].



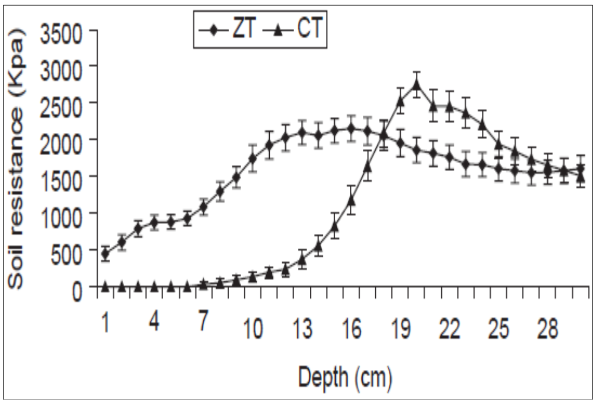
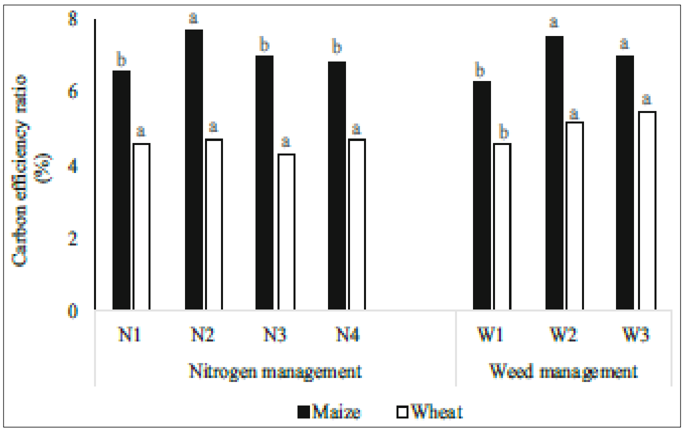


Fig 4(b): Effect of puddling on seed distribution of *P. minor* and *R. dentatus* [Source: Chhokar *et al*., 2007] [12].
Fig 4(c): Soil strength under ZT and CT [Source: Chhokar *et al*., 2007] [12].

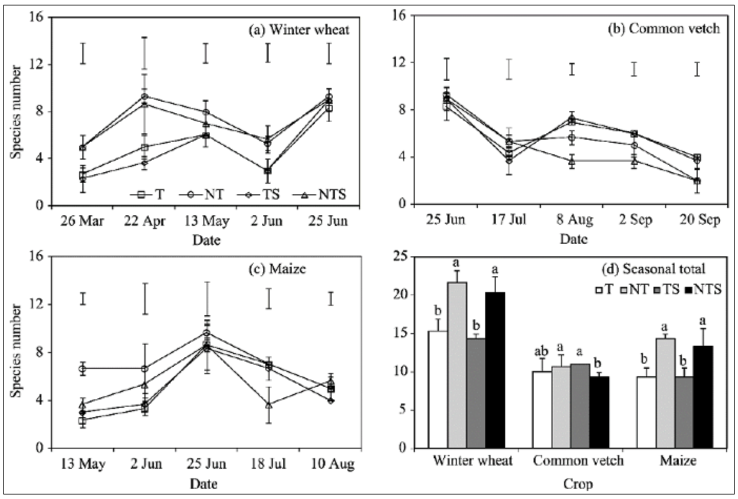
Oyeogbe *et al*. (2017) [33] revealed that the carbon efficiency ratio (CER) refers to the efficiency of carbon storage in soil (i.e., carbon fixed over the carbon emitted), which was affected by N and weed management effects [Fig.5a]. The NDVM-guided N fertilizations increased CER by 3–17% compared to whole N at sowing in maize, whereas there was no effect of N fertilizer management in wheat. Among the weed management in maize, brown manuring and herbicide mixtures resulted in 11 and 19% higher CER, respectively, than the weedy check, while the pre- and post-herbicide applications in wheat resulted in 16–22% higher CER compared to weedy check.

Yang *et al*. (2018) [41] found that no-tillage increased the number of weed species and weed density in most of the crops, while stubble retention decreased weed density in maize and tended to suppress weeds in both no-tillage treatments (no-tillage and no-tillage + stubble retention). No-tillage led to an increase in the number of weed species in the weed seed-bank and tended to increase seed density during the spring growth of winter wheat, but it decreased seed density during post-vetch fallow. Stubble retention tended to reduce seed density during the spring growth of winter wheat and post-vetch fallow [Fig.5b]. Moreover, stubble retention affected weed density in maize only, where there were stubble retention × crop growth stage and stubble retention × tillage interactions. From spring growth until harvest in winter wheat, weed density increased before decreasing in the NT and NTS treatments, whereas it continued to increase through the growing season in the T and TS treatments, culminating in a sharp rise [Fig.5c]. Weed density was greater in the NT and NTS treatments than in the T and TS treatments. In common vetch, a sharp decrease in weed density in all treatments was followed by a gradual, but steady decline in the NT and NTS treatments, whereas a subsequent increase was followed by a steady decrease in the T and TS treatments [Fig.5c]. For maize, weed density increased and then decreased in all treatments except for the NTS treatment, where it gradually and steadily decreased [Fig.5c]. Weed density was greater in the NT and NTS treatments than in the T and TS treatments before June. After June, weed density in the treatments was in the following order: T>NT>TS>NTS. In general, weed density was increased by the no-tillage treatments (NT and NTS) in winter wheat and common vetch, but it tended to be reduced by the retention of stubble [Fig.5c]. Moreover, it was also reduced by stubble retention in maize.



(a)

Fig 5(a): Carbon efficiency ratio (CER) in the maize–wheat system as affected by N and weed management [Source: Oyeogbe *et al*., 2017] [33].



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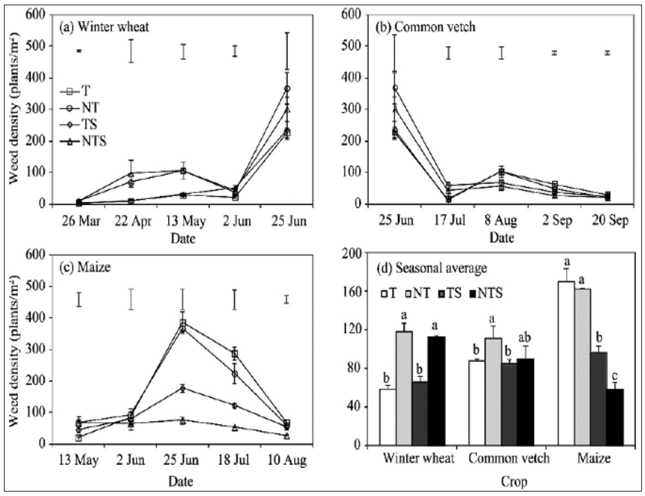


(c)

Fig 5(b, c): Number of weed species during the growth period of winter wheat (a), common vetch (b) and maize (c), and the total number of species across the whole season (d) under conventional tillage (T), no-tillage (NT), conventional tillage + stubble retention (TS) and no-tillage + stubble retention (NTS) treatments [Source: Yang, *et al*., 2018] [41].

Weed density during the growth period of winter wheat (a), common vetch (b) and maize (c), and weed density averaged over the whole season (d) under conventional tillage (T), no-tillage (NT), conventional tillage + stubble retention (TS) and no-tillage + stubble retention (NTS) treatments [Source: Yang, *et al*., 2018] [41].

Table 1: Herbicide residual in soil after crop harvest in respective years [Source: Oyeogbe *et al*., 2017] [33].

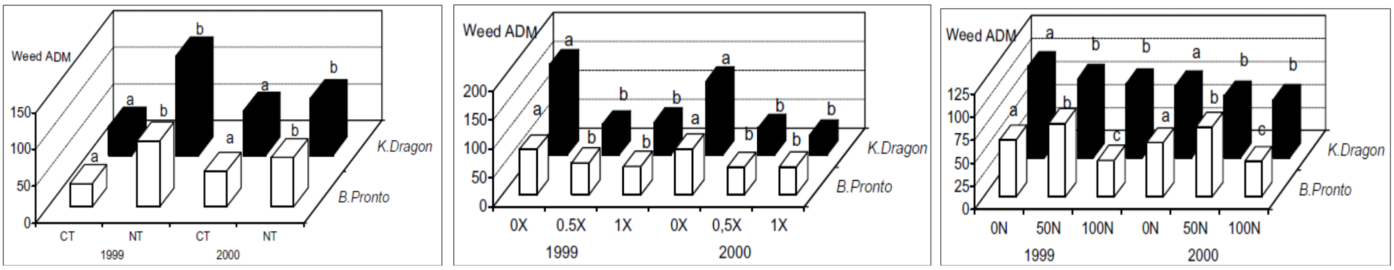
Weed management	Maize		Wheat					
	Atrazine (g/ha)	Pendimethalin (g/ha)	Pendimethalin (g/ha)		Carfentrazone-ethyl (g/ha)		Clodinafop-propargyl (g/ha)	
	2013 and 2014	2013 and 2014	2013–2014	2014–2015	2013–2014	2014–2015	2013–2014	2014–2015
Weedy check (control)	–	–	–	–	–	–	–	–
HM	BDL	11.2 ± 0.3 and 10.1 ± 0.2	22.1 ± 0.3	33.6 ± 0.3	0.83 ± 0.03	0.85 ± 0.02	–	–
BM (maize) + HM (wheat)	–	–	–	–	0.55 ± 0.02	0.63 ± 0.01	BDL	BDL

HM herbicide mixture, *BM* brown manuring, *BDL* below detectable limit
— not applicable

Oyeogbe *et al*. (2017) [33] observed that the recovery rate of the herbicide residual in soil samples ranged between 78 and 94% at 1 ppm. Residues of atrazine were below the detectable limit at the end of the maize cropping season [Table1], whereas about 10– 11gha^{-1} of pendimethalin residue was detected in 2013 and 2014, respectively. This indicated that the pendimethalin remaining in soil was about 1.5% of the applied dose.In wheat cropping seasons, residues of the pre-emergent herbicide mixtures of pendimethalin and carfentrazone-ethyl ranged between 22–34 and 1gha^{-1} in both years, whereas the post-emergent carfentrazone-ethyl residual in soil was about 1gha^{-1}, and clodinafop-propargyl was below the detectable limit. This showed that about 2–3% of pendimethalin and 3–4% of carfentrazone-ethyl persisted as active residues in the soil after crop harvest.

Residues of pendimethalin and carfentrazone left at the time of crop harvest were less than 5% of the dose applied. Residues of atrazine and clodinafop were below detectable levels. This indicates that these herbicides were degraded sufficiently during crop-growing periods and were safe to the next crops that would be grown in sequence. Sondhia *et al*. (2014) [39] reported that atrazine, pendimethalin, and clodinafoppropargyl dissipate rapidly with little or no residue in the post-harvest soil. Our studies could indicate that the presence of brown manuring as cover crop decreased weed interference and herbicide dose and residue in soil (Sondhia *et al*., 2014; Vivek *et al*., 2018) [39]. Yet, organic residue soil cover in CA can affect herbicide absorption, thereby resulting in low herbicide efficacy or rapid biodegradation (Flower *et al*., 2013) [20]. Lower herbicide use in conservation agriculture has important implications for sustainable crop production intensification.

Acciaresi *et al*. (2003) [1] also found that weed ADM varied across years. Conversely to crop biomass, the main tillage effects in both years were lower weed biomass production under CT in both varieties, and a lower production in 1999 than in 2000 [Fig.6a]. These results are in agreement with Arshad *et al*. (1995) [3] who found a higher weed mass in NT than in CT. In no-tillage systems, the weeds seeds remain in the upper layer and immediately contribute to infestation. This could explain the greater biomass registered in NT than in CT plots, despite the relatively drier 1999 spring. However, Buhler (1995) [4] determined that the effect of surface residue on weed dynamics appears to be complex and controlled by interacting factors (soil type, weed species, quality and type of residue, allelopathy and environmental conditions). Moreover, no differences were observed between the effects caused by the 1x and 0.5 x doses in the crop ADM. Conversely, significant differences amongst these herbicide rates and 0x were observed for crop variables. K. Dragon had higher tolerance to weed competition than B. Pronto for the herbicide rates evaluated. This effect was visualised in the 0x plots, where K. Dragon, despite the higher weed ADM obtained [Fig.6b], showed a higher grain yield than B. Pronto during both years. However, the two fertilization levels significantly lowered weed biomass when competing with K. Dragon [Fig.6c]. As in the tillage treatment, when nitrogen was added full rate (100 N) the cvs presented differences in tolerance to competition against weeds. Highest grain yield was obtained by K. Dragon, despite the higher weed ADM observed in the full rate plots [Fig.6c].



(a) (b) (c)

Fig 6(a): Weed above-ground dry matter (ADM, g m^{-2}) under two tillage systems (CT: conventional tillage, NT: No-tillage) [Source: Acciaresi *et al*., 2003] [1].

Fig 6(b): Weed above-ground dry matter (ADM, g m^{-2}), as affected by herbicide rates (0X: no herbicide, 0.5X: half rate and 1.0X: normal rate) [Source: Acciaresi *et al*., 2003] [1].

Fig 6(c): Weed above-ground dry matter (ADM, g m^{-2}) as affected by fertilizer rates (0N: no fertilizer applied, 50N: 50 kg N ha^{-1} and 100N: 100 kg N ha^{-1}) [Source: Acciaresi *et al*., 2003] [1].

Herbicide resistant weeds in wheat in northern plains

Little seed canary grass (*Phalaris minor*) is the most problematic grass weed of irrigated wheat in India. The problem of this weed emerged after "green revolution" (mid-seventies) due to adoption of dwarf high yielding varieties, improved irrigation and fertiliser facilities. During the late 1970s, Indian wheat farmers were so troubled by heavy infestations of this weed that many farmers ploughed down their immature wheat crop or harvested as forage. For its control in the late seventies *isoproturon* was recommended and from 1980 to 1990, isoproturon kept *P. minor* and other weeds under control and farmers realised the full advantage of the high yielding albeit less competitive, dwarf wheat. However, during early nineties, *P. minor* evolved isoproturon resistance due to sole dependence on this herbicide (Malik and Singh, 1995) [26]. After isoproturon resistance evolution, there were again instances when wheat farmers were forced to harvest their immature wheat crop as fodder in the absence of effective alternate herbicides (Malik and Singh, 1995) [26]. The factors which favoured the development of isoproturon resistance in India are mono-cropping (Rice-wheat), mono-herbicide (Isoproturon use only) and under dosing. For the control of isoproturon resistant *P. minor* five herbicides (tralkoxydim, diclofop, clodinafop, sulfosulfuron and fenoxaprop) were recommended during late nineties but farmers mainly accepted sulfosulfuron and clodinafop. Now again the *P. minor* has evolved resistance against these herbicides. The multiple resistance problems at few locations are so severe that it is causing huge grain yield reductions. For control of isoproturon resistant, *P. minor* clodinafop, fenoxaprop-p-, pinoxaden, mesosulfuron, flufenacet, metribuzin, pendimethalin, trifluralin and sulfosulfuron canbe used. For control of clodinafop resistant populations of, *P. minor* sulfosulfuron, mesosulfuron, flufenacet, metribuzin, pendimethalin and trifluralin can be used. For controlling sulfosulfuron resistant populations, clodinafop, fenoxaprop-p, pinoxaden, flufenacet, metribuzin, pendimethalin, trifluralin can be used. However, major concern is where *P. minor* has evolved resistance against clodinafop and sulfosulfuron and under such conditions we have limited options and effective herbicides are flufenacet, metribuzin, pendimethalin and trifluralin. Pyroxasulfone is another herbicide thatcontrols the multiple resistant populations (resistant to isoproturon, clodinafop and sulfosulfuron) of. However, *P. minor* the metabolic nature of isoproturon resistance can make most of the herbicides as ineffective by further extension of resistance. This has already happened in annual ryegrass (*Lolium spp*.) in Australia (Burnet, 1991) [5].

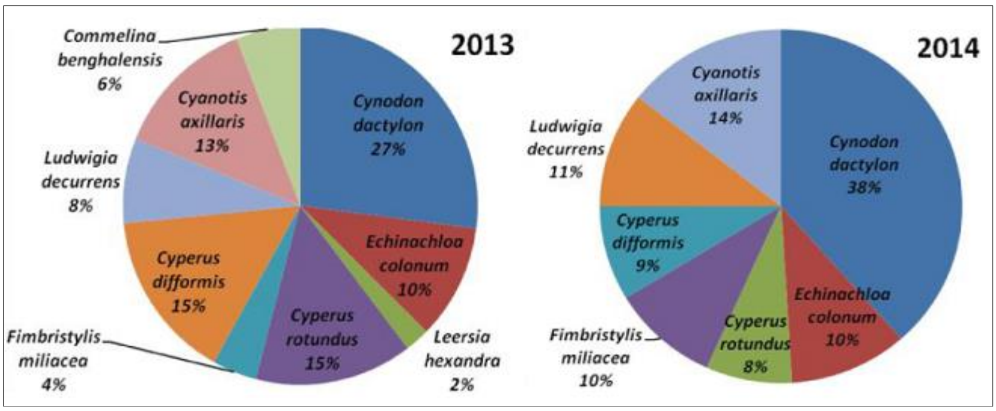
Recently, *Rumex dentatus* has also evolved resistance against metsulfuron and has shown cross résistance to pyroxsulam and mesosulfuron+iodosulfuron. In near future the resistance problem may be further aggravated if solely depend on herbicides for weed control. Therefore, management strategies must be developed to prevent selection and spread of herbicide resistant populations. The different ways by which we can reduce the selection pressure for resistant populations are alternative herbicide, herbicide mixture, crop rotation and other agronomic practices providing the crop with a competitive edge over the weed (Wrubel and Gressel, 1994) [43]. Crop rotation and herbicide rotation helps in lowering the selection pressure (Gressel and Segel, 1990) [22]. It is also necessary to follow sanitation practices (weed-free crop seeds, well-rotten manure and clean machinery). Where possible, consideration should also be given to applying manual weed control methods to remove weeds surviving the application of herbicide before seed-setting. The integration of non-chemical agronomic tactics (competitive variety, early sowing, higher seed rate, ZT, stale seed bed) with chemical weed control will help in minimising the impact of herbicide resistance on wheat production and farmers income.

Herbicide resistant crops

Herbicide resistance is the inherited ability of the plant to survive and reproduce following exposure to a dose of herbicide that would normally be lethal to the wild type. In a plant, resistance may occur naturally due to selection or it may be induced through such techniques as genetic engineering. The adoption of genetically modified (GM) crops has increased dramatically during the last 10 years and currently over 52 million hectares of GM crops are planted worldwide. Approximately 41 million hectares of GM crops planted are herbicide-resistant crops, which includes an estimated 33.3 million hectares of herbicide-resistant soybean. Herbicide resistant maize, canola, cotton and soybean accounted for 77% of the GM crop hectares in 2001. However, sugar-beet, wheat, and as many as 14 other crops have transgenic herbicide resistant cultivars that may be commercially available in the near future. There are many risks associated with the production of GM and herbicide-resistant crops, including problems with grain contamination, segregation and introgression of herbicide-resistant traits, market place acceptance and an increased reliance on herbicides for weed control.

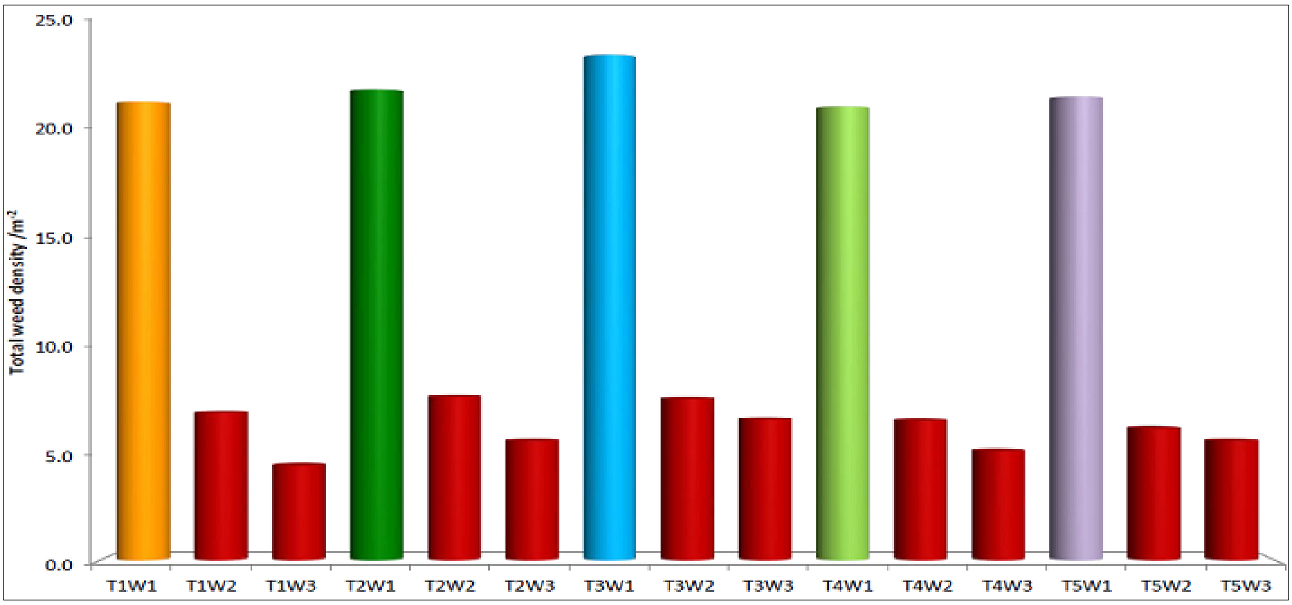
Taslima *et al*. (2018) observed that that tillage practice had a great influence on the availability of weed species and continuous practice of minimum tillage helped to reduce number of weed species after a certain period. However, sole application of herbicide was less effective to control all types of weed species than sequentially applied herbicides. Sequential application of pre- and late post-emergence, early post- and late post-emergence or pre-, early and late post-emergence herbicides controlled weeds by 46-98% and 43-95%, respectively in terms of weed density and biomass. Sequential application of pyrazosulfuron-ethyl followed by orthosulfamuron and butachlor + propanil provided the most effective and economic weed control under this new rice establishment practice. Moreover, the study suggested a range of effective herbicides for strip-tilled non-puddled wet season rice, but possible rotation of those herbicides in a sequential application is needed. Additionally, residue of those herbicides did not show any adverse effect on the succeeding crops of rice like wheat and lentil [Fig.7a].

Sapre, (2017) [35] also found that there was predominance of *Cyperus iria* (48.57%) and *Echinochloa colona* (21.88%) in rice as both had higher relative density. However, other weeds i.e., *Dinebra retroflexa* and *Caesulia axillaris* were also present in lesser numbers (7.33 and 5.19%) respectively. Similarly, *Medicago denticulata* was rampant in wheat crop as it had higher relative density (72.42%) as compared to other weeds *Phalaris minor* (22.08 %) and *Avena ludoviciana*. However, *Echinochloa colona* was only the major weed in greengram having 100% relative density [Fig.7b]. However, four weed species i.e. *Echinochloa colona, Cyperus iria, Phalaris minor* and *Medicago denticulata* were taken for weed seed bank study. It was found that, zero tillage practice ZT+S(R)-ZT (W)-ZT (M) and ZT+MR+S(R)-ZT+RR (W)-ZT+WR (M) had higher weed seed bank in upper soil (0-5 cm) than conventional tillage practices. But reverse was true in case of conventional tillage practices where rich weed seed bank was found in 5-10 cm soil depth in comparison to 0-5 and 10-15 cm soil depth. Herbicide application did not cause vertical distribution of weed seeds [Fig.7b]. However, weed seeds were higher in weedy check plots as compared to herbicidal treated plots at all soil depth.



(a)

Fig 7(a): Weed species composition of the weedy plots of strip-tilled non-puddled transplanted wet season rice in 2013 and 201 [Source: Taslima *et al*., 2018]



(b)

Fig 7(b): Total weed density under rice-wheat-mungbean cropping system as affected by different tillage and weed management practices [*Source*: Sapre, 2017] [35].

Tillage effect on weed abundance and diversity

Conventional tillage includes all tillage treatments that leave less than 15% of crop residues on the soil surface after planting the next crop, or less than 1,100 kg/ha of small grain residues throughout a critical erosion period. In general, such tillage techniques involve plowing or intensive tillage (Koller, 2003). Conservation tillage retains an amount of about 30% or greater of soil surface covered by crop residues and it includes four main types: mulch tillage, ridge tillage, zone tillage, and no-tillage (Carter, 2005). Crop management strongly affects the abundance and diversity of weeds and changes in tillage are likely to have a clear effect on the community structure (Nichols *et al*., 2015). Such changes in tillage may result in weed species shifts (Bilalis *et al*., 2003). Thomas *et al*. (2017) perennial species such as *Cirsium arvense* and *Sonchus arvensis* were associated with reduced- and zero-tillage systems, while annual species were associated with a range of tillage systems. Grey *et al*. (2017) showed that tillage alone can effectively control the potential invasive napier grass (*Pennisetum purpureum*) within a range from 12 to 33%. However, invasive weeds are inclined to recover rapidly when tillage is interrupted (Sheley *et al*., 2011). Shifts in plant communities are usually described or quantified by means of the various existing abundance and diversity indices. Armengot *et al*. (2016) observed an increasing trend in weed richness under reduced tillage compared with conventional tillage. However, crop type was recognized as the main driver of the shifts in the functional composition of weed communities. Armengot *et al*. (2015) also found that total weed coverage was higher under reduced tillage, though this result was not consistent for different crops. In particular, average abundance of perennials almost doubled overtime under reduced tillage, while yields did not show any difference between the different treatments. Higher weed abundance and density under conservation tillage have been also confirmed by other studies (Gruber and Claupein, 2009). Cardina *et al*. (2002) reported that in mouldboard plough plots the densities of *Amaranthus retroflexus* and *Veronica arvensis* were both lower compared to no-tillage plots.

Kakabouki *et al*. (2015) indicated that weed biomass and density in quinoa crop were influenced by the different fertilization and tillage treatments with tillage effects being species dependent. Similarly, total weed coverage and perennial coverage in reduced tillage treatments were two to three times greater compared with conventional treatments (Sans *et al*., 2011). Weed biomass in barley showed also higher rates in the conservation compared to the conventional tillage treatment (Vakali *et al*., 2011). Santín-Montanyá *et al*. (2013) reported that the abundance, diversity and evenness of the weed community in a wheat field, were greatly increased in no-tillage systems. Mulugeta *et al*. (2001) also confirmed that species richness was higher in long-term no-tilled fields than in tilled or short-term no-tilled fields. Furthermore, it is noted that less important weeds often become dominant after a period of no-tillage in which weed seeds are retained near the soil surface (Soane *et al*., 2012).

While current knowledge suggests that weed community composition will change in response to different tillage systems, the alterations in weed diversity of the community remain less clear. Bilalis *et al*. (2001) used both Simpson's and Shannon- Weiner's indices to verify the impact of three different tillage amendments on shifts in weed flora in a 3-year crop-rotation treatment. In all crops, apart from cotton, significant differences were found among the tillage systems. Three annual species prevailed in the conventional and minimum tillage systems (*Sinapis arvensis*, *Solanum nigru*m and *Tribulus terres*tris), while one perennial species (*Malva* sp.) prevailed in the no-tillage system. Mas and Verdú (2003) reported that the highest values of Shannon-Wiener diversity index were noted under no-till conditions. Conservation tillage systems resulted in increased weed diversity compared with conventional mouldboard plough-based tillage systems. Some species, such as *Capsella bursa-pastoris* and *Torilis nodosa*, were dominant in the reduced tillage systems (no tillage, no-tillage with paraplow and minimum tillage), while two different weed species (*Polygonum aviculare* and *Phalaris paradoxa*) were the dominant ones in the conventional system.

In addition, Menalled *et al*. (2001) reported that aboveground weed biomass, species density, and diversity lowest values were obtained under conventional tillage system, intermediate values under no-tillage system, and highest values under low-input and organic systems. Moreover, it was observed that annual grass species, such as *Digitaria sanguinalis* and

Panicum dichotomiforum dominated the no-tillage system. It is noteworthy to mention that different diversity pattern with regards to tillage among crops suggests that other agronomic practices and environmental factors may interact in a complex way with tillage and affect the weed diversity within communities (Légère *et al*., 2005).

Verma *et al*. (2015) [40] revealed that in many rural Indian communities it has becomes increasingly difficult to hire labour for weeding and other farming activities, due to a swindling labour force as consequence of outmigration of the male population. As a result farm operations are often delayed and labour costs have increases. The situation calls for labour saving weed management practices for sustainable crop production. Depending on weed type and crop weed competition, it reduces yield up to 96.5 per-cent and sometime total crop failures reported by several researchers given in Table 2.

Table 2: Yield reduction caused by weed in different crops [Source: Verma *et al*., 2015] [40].

Name of crops	% Yield reduction	Reference
Direct seeded paddy	45-90	Singh (20140
Transplanted paddy	15-38	Singh (2014)
Maize	28-93	Malviya and Singh (2007); Singh (2014)
Sorghum	6-40	Singh (2014)
Finger millet	26-27	Pradhan *et al*. (2013)
Redgram	20-47	Singh (2014)
Soybean	40-60	Jha and Soni (2013); Singh (2014)
Wheat	26 - 38	Das (2008); Verma *et al*. (2008); Das *et al*. (2012) and Kewat (2014)
Oat	26-30	Kewat (2014)
Lucerne	50-90	Revathi *et al*. (2012)
Barley	20-25	Kewat (2014)
Chickpea	15-25	Kewat (2014)
Lentil	20-30	Kewat (2014)
Pea	20-30	Kewat (2014)
Mustard	15-30	Kewat (2014)
Linseed	30-40	Kewat (2014)
Safflower	35-60	Kewat (2014)
Groundnut	20 - 50	Rathore (2014)
Sesame	50-75	Bhadauria *et al*. (2012); Duary and Hazra (2013);Rathore (2014)
Sun flower	30-64	Sumathi *et al*. (2009); Rathore (2014)
Castor	15-25	Rathore (2014)
Cotton	74-96.5	Ayyadurai and Poonguzhalan (2011)
Niger	30-33	Rathore (2014)
Jute	58-70	Ghorai *et al*. (2013)
Coriander	20-50	Yadav *et al*. (2013)
Sugarcane	40-67	Chauhan and Srivastava (2002); Pratap *et al*. (2013)
Egyptian clover	30-40	Pathan *et al*. (2013)
Brinjal	49-90	Reddy *et al*. (2000); Kunti *et al*. (2012)
Tapioca	40-50	Lebot (2009); Prameela *et al*. (2012)

Seeding rate

Crop density is an important component of the crop's ability to compete with weeds (Arvadiya *et al*., 2012). Variation in the seed rates and high seed rate significantly influenced weed population and their dry weight by securing an optimum plant population (Meena *et al*., 2010) [28], which shows excellent smothering effect on weeds (Sharma and Singh, 2011) and improving productivity and profitability of the crop.

Methods and Levels of Fertilizer Application

Fertilizers alter the nutrient level in the agro-ecosystems and therefore they may directly affect weed population dynamics and crop weed competitions (Babu and Jain, 2012). Nevertheless, nutrients clearly promote crop growth but benefit weeds more than crops (Upasani *et al*., 2013). Strong effects can be observed by manipulating fertilizer timing, dosage, and placement in order to reduce weed interference in crops (Dubey, 2014). Appropriate timing of N mineral fertilization has been proposed in integrated cropping systems as a mean to unbalance nutrient competition between crop and weeds to the benefit of the former (Das and Yaduraju, 2007) [18]. Placement of fertilizer significantly reduced the density and dry biomass of weed and produced higher grain yield than broadcast method of fertilizer application (Lodha *et al*., 2010). Wan *et al*. (2012) evaluated the influence of different fertilization on weed diversity in rice paddy fields. Five fertilization treatments (no fertilization or NOF, PK, NP, NK, and NPK) were applied and according to the results the following models were occurred: PK > NOF > NK > NP >NPK, PK > NOF > NK > NP > NPK, NPK >NP > NK > NOF > PK and PK > NOF > NK > NP>NPK for species richness, species diversity, dominance and evenness of community, respectively. Than *et al*. (2017) studied the effect of different fertilizer treatments on weed densities and richness indices. The results showed that the N and P fertilizer application had a more significant impact on weed community compared to the K application. In another study, the growth responses of common crops and weeds with addition of composted poultry manure (CPM) were compared (Little *et al*., 2015).

Irrigation

Optimum time and number of irrigation reduces the density and weight of weeds (Verma, 2014). Singh and Singh (2004) [36] reported that pre-sowing irrigation reduced the dry weight of C. album and C. murale by 21 and 25%, respectively, and subsequently grain yield was 12% higher over post sowing irrigation. Wheat irrigated at CRI+ tillering + flowering stage reduced the dry weight of *Phalaris minor* over crop irrigated at CRI+ tillering + flowering+ dough, CRI + tillering, CRI + flowering and at CRI stage, respectively (Das and Yaduraju, 2007) [18]. Irrigation at 0.4 IW: CPE in Isabgul (Parmar *et al*., 2010), 1.25 IW: CPE in wheat (Nadeem *et al*., 2010) [30] and 0.6 IW: CPE ratio in fenugreek (Mehta *et al*., 2010) [28] resulted lower weed population and higher yield over 0.8 and 1 IW: CPE.

Mechanical weed Control

Most mechanical weed control methods, such as hoeing, tillage, harrowing, torsion weeding, finger weeding and brush weeding, are used at very early weed growth stages (Kewat, 2014). Hoeing can be effective on older weeds and remains selective, many mechanical control methods become difficult after the cotyledon stage and their selectivity decreases with increasing crop and weed age. Thus, if the weeds have become too large, an intensive and aggressive adjustment of the implements is necessary to control the weeds, and by doing this one increases the risk of damaging the crop severely. Stopping tillage practices has a positive impact on weed populations, because it can influence the weed seed viability and distribution and it has a strong impact on weed emergence by burying weeds in the soil (Vasileiadis *et al*., 2006) Table 3. Conservation tillage leaves more weed seeds on the surface, whereas high disturbance systems bury weeds. Weed seeds left on the surface are generally more susceptible to decay and ultimately reduce weeds seed banks (Chauhan *et al*., 2006), it allowed early sowing and thus the competitive advantage remains in favour of crop not for weeds (Sharma, 2014), lower emergence in conservation tillage might be due associated with higher soil strength (Dev *et al*., 2013).

Table 3: Weed seed population in the top 20 cm as affected by tillage sequence and weed management [Source: Verma *et al*., 2015] [40]

Tillage sequence	Weed seed as affected by weed management			Mean
	Weedy check	Herbicide	Herbicide + one hand weeding	
Zero tillage- Zero tillage	70	89	20	60
Zero tillage- conventional tillage	92	92	34	72
Conventional tillage- Zero tillage	80	43	31	51
Conventional tillage-conventional tillage	112	81	25	73
Mean	88	76	27	

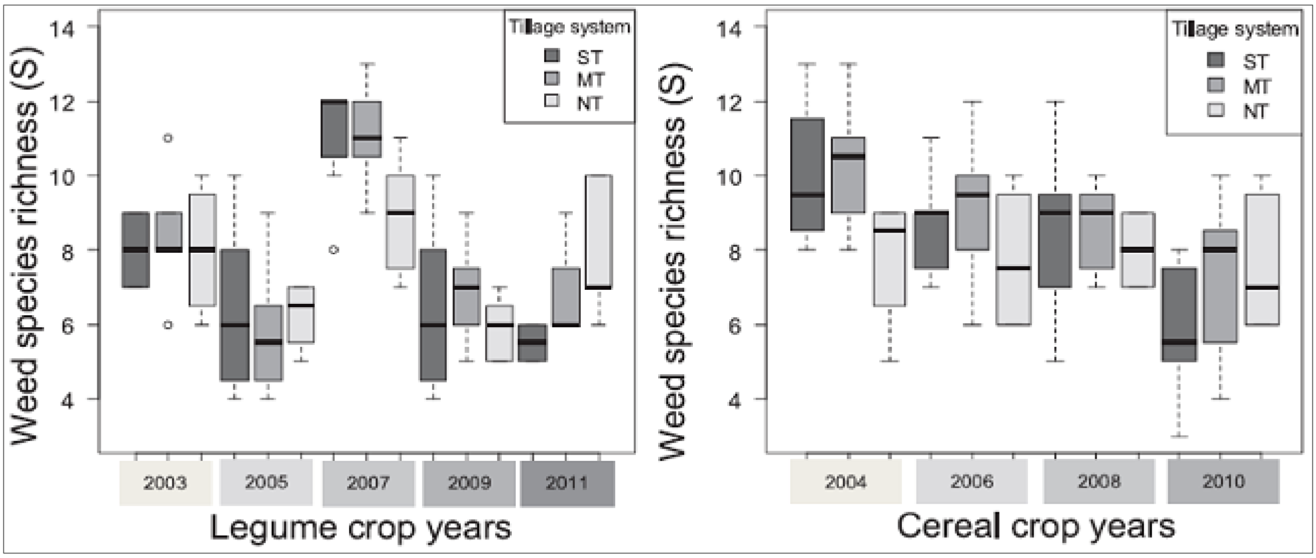
Sowing/planting methods

Weed population and its dry weight are significantly influenced by methods of sowing and planting of crops (Dev *et al*., 2013). Zero-till and FIRB sowing recorded lower weeds density with higher grain yield in wheat (Ahmed *et al*., 2010) over conventional tillage and strip till drill system, in maize (Chopra and Angiras, 2008) over conventional tillage and flatbed system and in lentil (Manjunath *et al*., 2010) over flat sowing. This is because of avoidance of wetting of whole cropped soil surface in bed sowing and the weed did not find congenial moisture conditions at the surface to germinate (Sharma, 2014). In zero till seeding by Happy Seeder machine with stubble mulching, undisturbed inter row space, where seeds lying at lower depths did not germinate (Bhullar *et al*., 2006) and it saves time and energy (Yadav *et al*., 2013). BBF method of sowing provides favourable environment for the growth and development of crop and reducing weed population over flat bed and ridge furrow methods (Jha and Soni, 2013). Bidirectional sowing in wheat gives fewer weeds compared to unidirectional sowing although seed rate is same (Singh *et al*., 2012). Transplanting under puddle condition had given detrimental impact on weed growth and resulted lowest producer of weed dry weight over direct sowing with zero till drill under unpuddled wet seed bed, direct drum seeding of pre-germinated seeds under puddle conditions, unpuddled transplanting (Singh *et al*., 2013), SRI (Hassan *et al*., 2010), whereas, drum seeding + green manure significantly reduced weed density in direct seeded rice over drum seeding alone and broad casting (Sangeetha *et al*., 2009).

Planting pattern

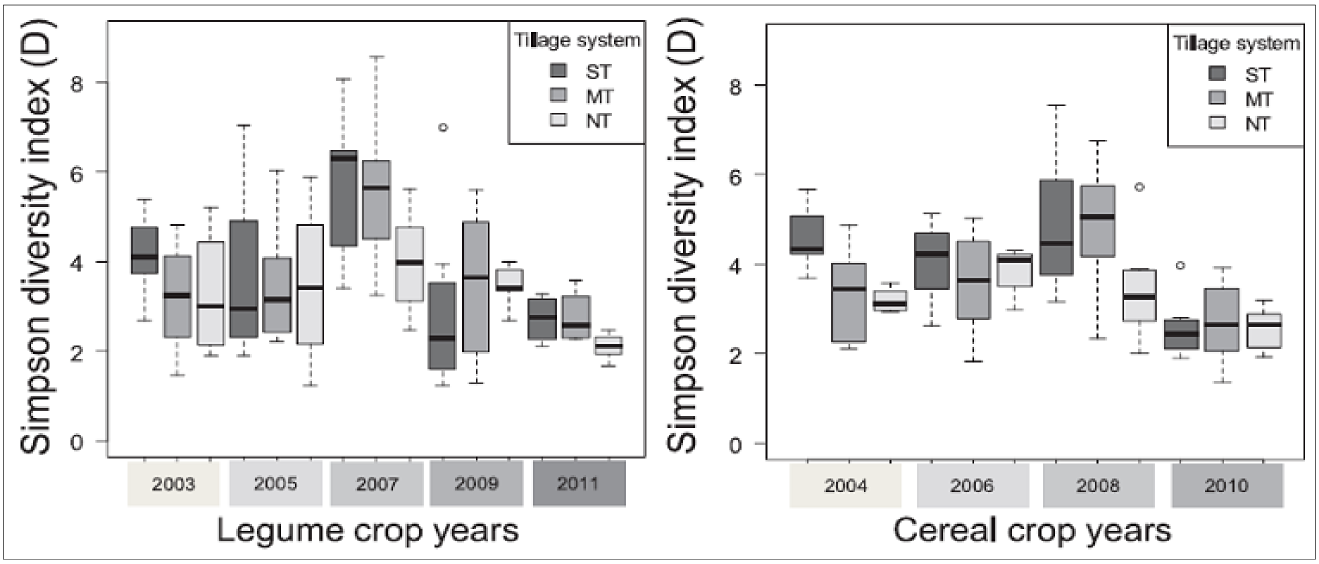
Planting pattern, which modifies the crop canopy structure and micro climate, in combination with weed management practices, may influence the weed infestation to a great extent (Dwivedi *et al*., 2012) and hypothesized that increased crop density (Kewat, 2014), reducing row spacing and spatial uniformity can increase weed suppression, because the competitive ability of crops with weeds is improved (Singh, 2014). In a perfectly uniform grid pattern, where the distance between individual crop plants within the row and between the rows is equal, competition with weeds will begin sooner than in a row pattern and competition between individual crop plants will be delayed as long as possible (Singh and Singh, 2006). Closer row spacing will improve crop competition for limited resources due to a rapid canopy closure (Nagamani *et al*., 2011) reducing weed seedling growth and soil weed seed bank (Arvadiya *et al*., 2012). Dry matter of weeds in wheat was significantly the lowest under bi-directional row orientation followed by North-South row orientation, cross sowing at 22.5x22.5 cm and highest under normal 22.5cm (Chaudhary *et al*., 2013), this might be due to better smothering effect (Singh, 2014).

Alarcón *et al*. (2018) [2] reported that cereals are more competitive and may act as a stronger biotic filter on weed community than do legume crops. However, this was reflected in the reduced weed emergence observed in the legume crop years - the effect of the control exerted by the cereal crop in the previous season. Subsequently, legumes might permit an increase in seed production by less abundant weed species, which might contribute towards a refilling of the soil seed bank [Fig.8a]. Tillage effects were greater in the cereal crop than in grain legumes. Weed community composition was significantly affected by the interaction year × tillage system in both crops, but no weed composition could be unequivocally associated with any tillage system on its own. In cereals, NT registered the lowest richness values while diversity (D) was higher in ST. However, the D value associated with the cereal crop was affected by the interaction year × tillage system. However, the tillage system used did not affect the D value associated with the legume crop [Fig.8b].



(a)

Fig 8(a): Weed species richness (S) by year and tillage system (subsoil tillage (ST), minimum tillage (MT) and no tillage (NT)) observed along in a legume-cereal crop rotation over 9 years [*Source:* Alarcon *et al*., 2018] [2].

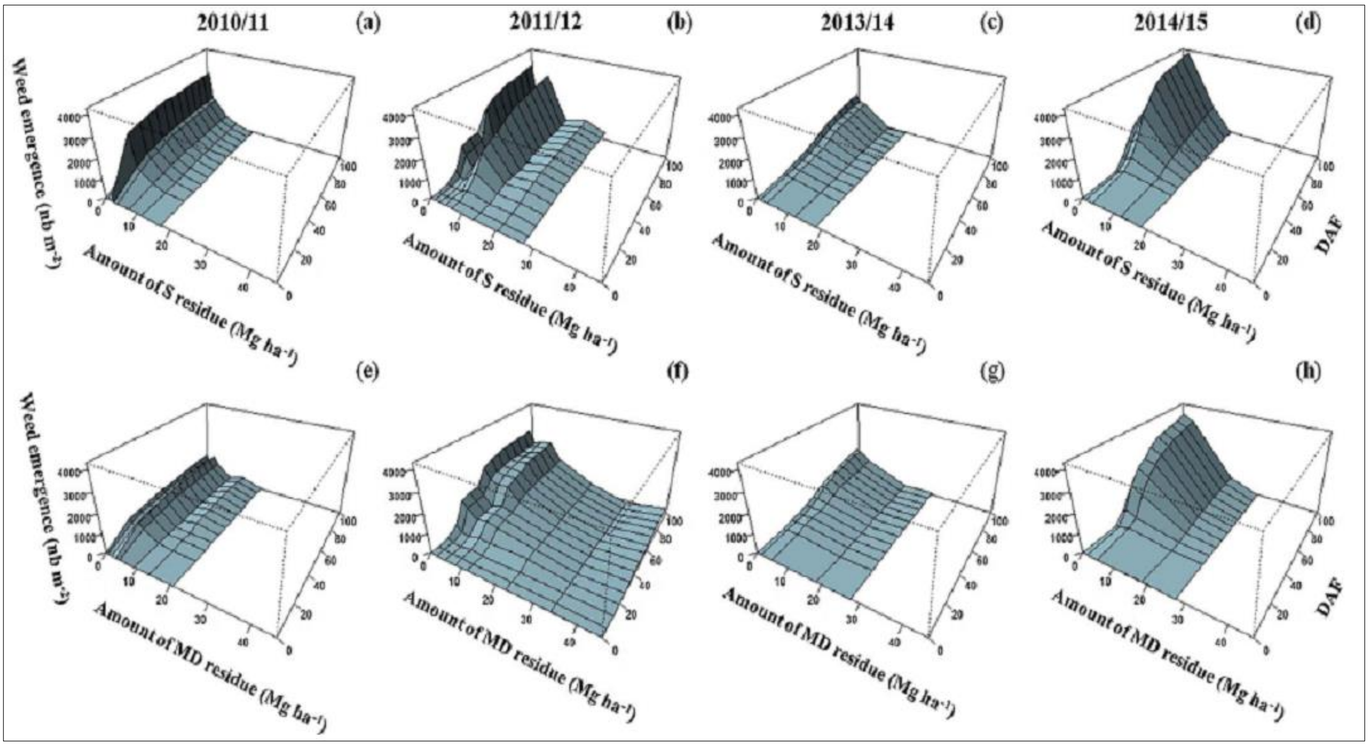


(b)

Fig 8(b): Simpson diversity index (D) observed for weed communities by year and tillage system systems (subsoil tillage (ST), minimum tillage (MT) and no tillage (NT)) observed along in a legume-cereal crop rotation over 9 years [Source: Alarcon *et al*., 2018] [2].

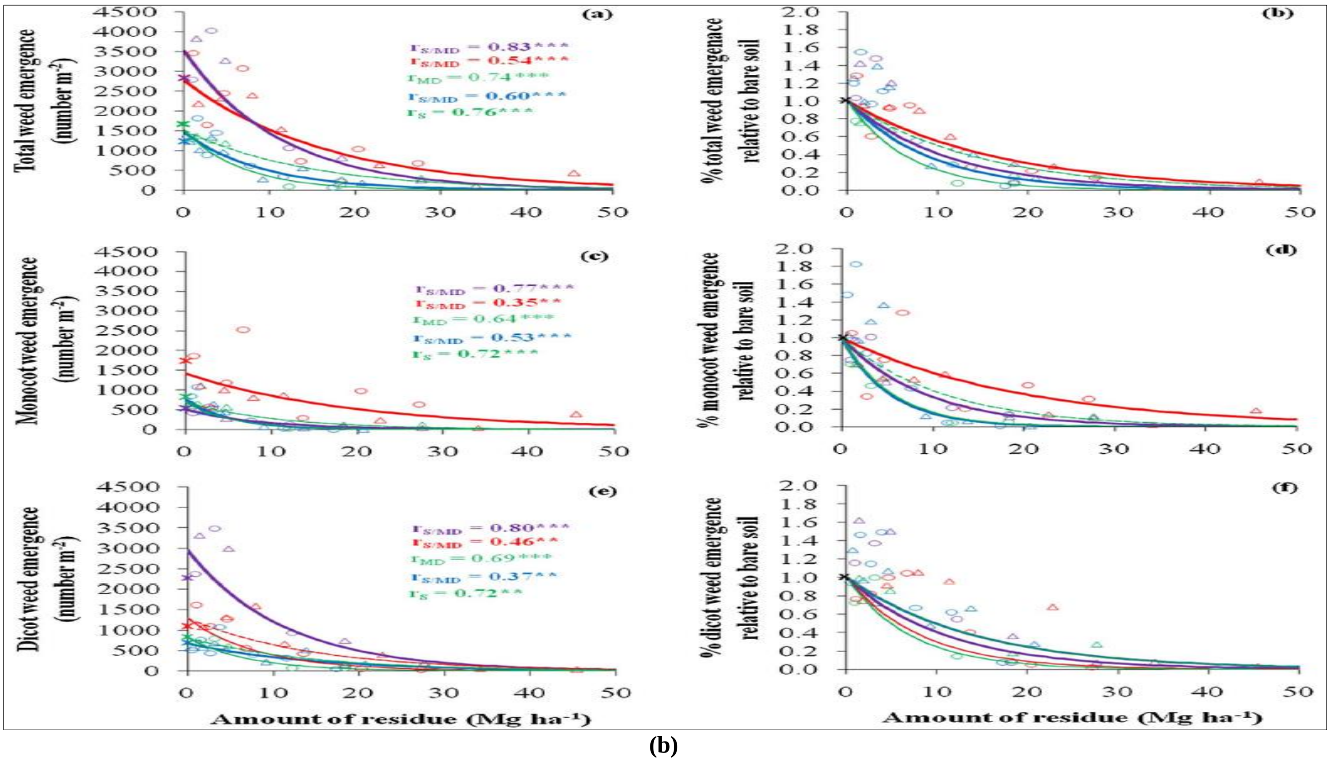
Ranaivosona *et al*. (2018) [34] reported that without rice crop a large proportion of the total weed emergence on bare soil was reached before 30 DAF, 918 seedlings m^{-2} and 1408 seedlings m^{-2} in respectively year corresponding to 74% and 50% of total weed emergence [Fig.9a]. Weed emergence was in general low compared to the other years and increased continuously during the growing season for amounts of residue less than 10 Mg ha^{-1}. In year 4, weed emergence occurred in general mainly between 25–55 DAF irrespective of the type of residue, which corresponded to the period of high and continuous rainfall [Fig.9a]. Monocot weed emergence was significantly reduced in treatments with more than 3.2 Mg ha^{-1} of S residue and 18.3 Mg ha^{-1} of MD residue between 27–41 DAF, whilst 18.3 Mg ha−1of S residue and 27.6 Mg ha^{-1} of MD residue were needed between 20–100 DAF for the same effect. Dicot weed emergence was significantly reduced as compared to the bare soil between 69–83 DAF in treatments with more than 12.2 Mg ha^{-1} of residue irrespective of the type of residue, whereas the amount needed increased to 18.3 Mg ha^{-1} of residue at 90 and 100 DAF for MD residue. In year 4, total weed emergence was significantly higher as compared to the bare soil in treatments with 3.2 Mg ha^{-1} of S residue and 4.8 Mg ha^{-1} of MD residue at 25 DAF. Between 39–100 DAF, it was significantly reduced in treatments with more than 12.2 Mg ha^{-1} [Fig.9a]. Ahmed *et al*. (2007) found a significant decrease of weed biomass with 4 Mg ha^{-1} of wheat straw residue; Bilalis *et al*. (2003) with 5 Mg ha^{-1} of wheat straw and Campiglia *et al*. (2012) with 5 Mg ha^{-1} of oat residue.

However, cumulative weed (total, monocots and dicots) emergence at 100 DAF declined with increasing amount of residue for both types of residue during the four growing seasons following exponential decay functions [Fig.9b]. With respect to cumulative dicot weed emergence, the interactive effect of amount and type of residue was significant. For example, in year 3, 10 Mg ha^{-1} of S residue reduced emergence of dicots by 75% as compared to the bare soil, whilst the same amount of MD residue reduced it only by 50% [Fig.9b].



(a)

Fig 9(a): Total weed emergence (number of seedlings m^{-2}) from the first rain that triggered weed emergence to 100 DAF during the four growing seasons depending on the amount of residue (Mg ha^{-1}) for the two types of residue [Source: Ranaivosona *et al*., 2018] [34].

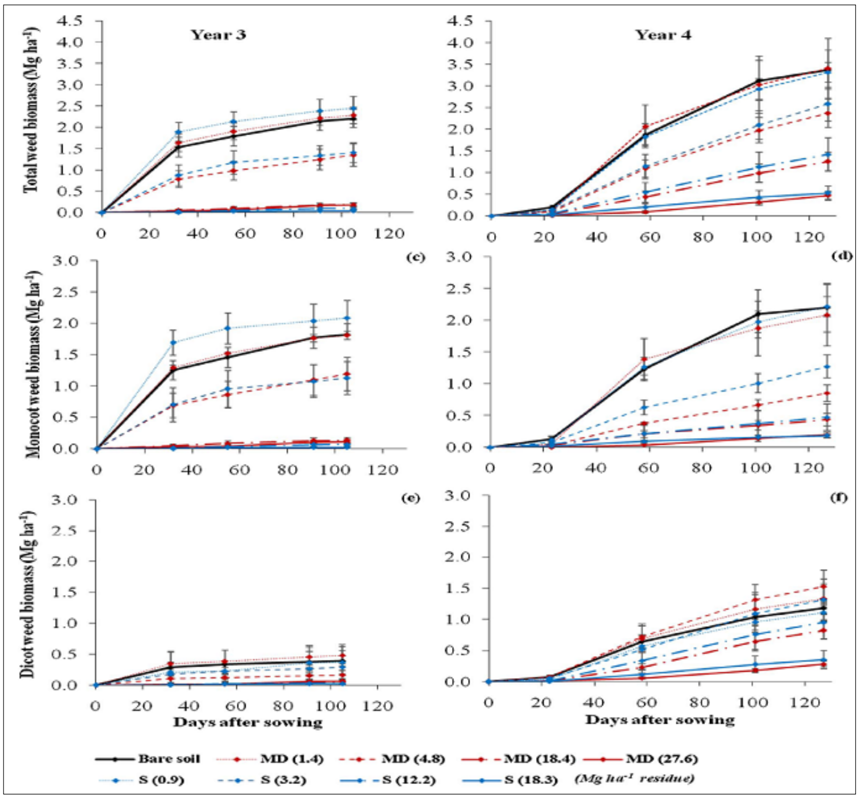


(b)

Fig 9(b): Relationship between absolute cumulative weed emergence (number of seedlings m^{-2}) and cumulative weed emergence relative to that on bare soil and the amount of residue [Source: Ranaivosona *et al*., 2018] [34]

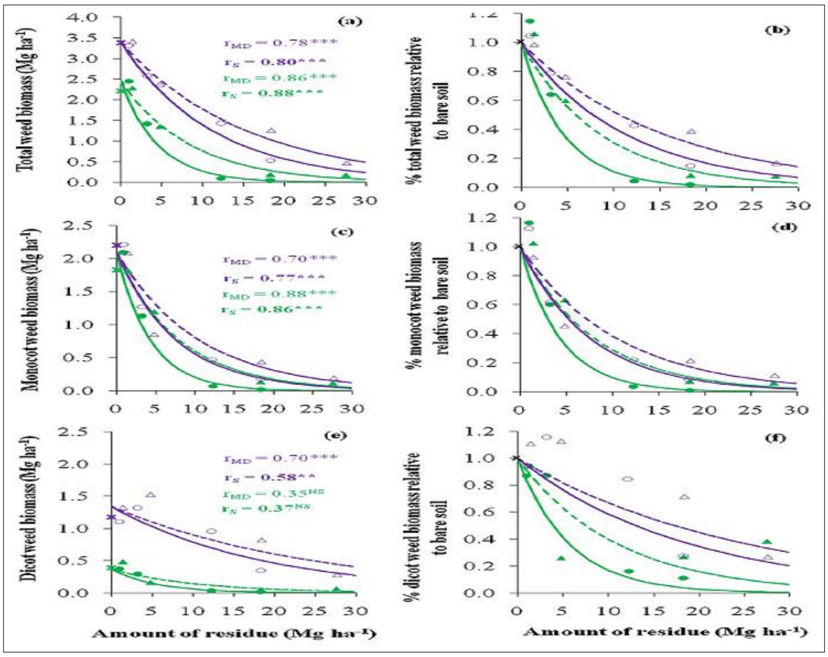
Dynamics of weed biomass under bare soil during the rice growing season were different between year 3 and year 4 [Fig.10a]. In year 3, more than 70% of total weed biomass was reached from the second weeding onwards (55 DAS). Thereafter, from 60 DAS, increase of total weed biomass was relatively low [Fig.10a]. In contrast, in year 4 a continuous increase of total weed biomass was observed from the first to the last weeding operation with the largest increase between 20–100 DAS [Fig.10a]. In year 3, at the minimum 4.8 Mg ha^{-1} of MD residue and 12.2 Mg ha^{-1} of S residue significantly reduced total weed biomass as compared to the bare soil from the first to the last weeding. Total weed biomass production was less than 0.2 Mg ha^{-1} for treatments with more than 12.2 Mg ha^{-1} of both residue types from the first to the last weeding [Fig.10a]. Biomass of monocot weeds was significantly reduced as compared to the bare soil with more than 18.4 Mg ha^{-1} of MD residue and 12.2 Mg ha^{-1} of S residue from the first to the last weeding date, whilst mulching had no significant effect on dicot weed biomass [Fig.10a]. Biomass of monocot weeds was significantly reduced as compared to the bare soil with more than 4.8 Mg ha^{-1} of both residue types from the second to the last weeding date [Fig.10a]. Surface residues (S or MD) had no significant effect on biomass of dicot weeds at the first and second weeding, whilst more than 18.3 Mg ha^{-1} of both residue types significantly reduced dicot weed biomass at the third and fourth weeding operation [Fig.10a].

Moreover, cumulative weed (total, monocots, dicots) biomass production at 100 DAF decreased with increasing amount of residue for both types of residue (S and MD) during the two growing seasons (year 3 and 4) following exponential decay functions [Fig.10b]. In year 3, cumulative monocot weed biomass was reduced by 91% as compared to the bare soil with 10 Mg ha^{-1} of S residue, whilst it was reduced only by 72% with the same amount of MD residue. The interactive effect of amount and type of residue on cumulative dicot weed biomass was not significant during the two growing seasons [Fig.10b].



(a)

Fig 10(a): Evolution of weed biomass production during growing seasons in relation to the type of residue and the amount of residue for total, monocot and dicot weeds [Source: Ranaivosona *et al*., 2018] [34].



(b)

Fig 10(b): Relationship between absolute cumulative weed biomass and cumulative weed biomass relative to the bare soil and the amount of residue for total, monocot and dicot weeds [*Source*: Ranaivosona *et al*., 2018] [34].

Conclusion

Weeds are location specific and the nature and intensity of weed flora are usually governed by the ecosystems under which it is grown. There is need to give fine tuning to the low cost weed management technology i.e. conservation agriculture which involving stale seed bed technique, suitable aerobic genotypes, cultural, physical, and mechanical and use of low doses of herbicides for different ecosystems in the different regions. More research is needed to develop ecologically sustainable integrated weed management systems for small and marginal farmers. High yielding rice varieties suitable for DSR under different agro-climatic conditions must possess the desirable traits, *viz*. vigorous growth; weed suppressing ability, germinating ability under moisture stress, tolerant to micronutrient deficiency. There is need to improve the productivity of DSR which is low due to inadequate nutrient management, inefficient water management and problem associated with weed management. Irrigation water supply must be ensured at the sowing time and also at the same time special concern given on weed management. Organic amendments, cover crops (*Sesbania* culture) and live mulching (*Sesbania* co-culture) shall be integrated in DSR production technology to break the niches of weeds and sustain the DSR culture. The problem of weedy rice is coming up in direct seeding rice especially in canal irrigated direct seeded areas. Strategic approach in tackling this menace is very much required. There is also need to address broad spectrum herbicide formulation / jumbo formulations to save the cost of herbicide application because most of the Indian farmers are small and marginal. In general, conservation of tillage systems seems to be associated with higher weed richness and diversity, as the elimination of tillage creates more enhancing conditions for some weed species. However, there are cases where reduced tillage systems led to less diverse weed communities compared to more intensive tillage systems.

Although CA allows the use of external inputs excessive fertilizer and herbicide application are detrimental to agro-ecosystem sustainability. Improving crop productivity and weed control by fertilizer and herbicide usage can result in short-term benefits but have long-term environmental consequences. Adaptive N and weed management practices are priorities for sustainable CA intensification. Our focus is to decouple greenhouse gas emissions and herbicide residues from yield-related productivity, which is important for the intensification of CA. Weed growth and moisture stress, are among major constraints which affect the productivity of aerobic rice in many parts of the world, including fragile agro-ecosystems of the North West IGP of India. Data from various studies showed that no-till and mulch application reduced weed density and biomass, increased soil profile moisture storage, and enhanced water productivity. No-till and mulches stored more soil moisture in root zone through profile recharge and enhanced yield parameters. Further, mulches could effectively manage weed infestation in aerobic rice. Therefore, the cultivation of aerobic rice under no-till with residue retention and with brown manuring mulch application is a feasible strategy to suppress weeds, conserve soil moisture and enhances rice productivity for livelihood security of farmers in the North West IGP of India and perhaps other similar eco-region elsewhere.

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