Weed Management Strategies to Reduce Herbicide Use in Zero-Till Rice–Wheat Cropping Systems of the Indo-Gangetic Plains

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Virender Kumar, Samar Singh, Rajender S. Chhokar, Ram K. Malik, Daniel C. Brainard, and Jagdish K. Ladha*

In the rice–wheat (RW) systems of the Indo-Gangetic Plains of South Asia, conservation tillage practices, including zero-tillage (ZT), are being promoted to address emerging problems such as (1) shortages of labor and water, (2) declining factor productivity, (3) deterioration of soil health, and (4) climate change. Despite multiple benefits of ZT, weed control remains a major challenge to adoption, resulting in more dependence on herbicides for weed control. Alternative management strategies are needed to reduce dependence on herbicides and minimize risks associated with their overuse, including evolution of herbicide resistance. The objectives of this review are to (1) highlight and synthesize research efforts in nonchemical weed management in ZT RW systems and (2) identify future weed ecology and management research needs to facilitate successful adoption of these systems. In ZT RW systems, crop residue can play a central role in suppressing weeds through mulch effects on emergence and seed predation. In ZT rice, wheat residue mulch (5 t ha^{-1}) reduced weed density by 22 to 76% and promoted predation of RW weeds, including littleseed canarygrass and barnyardgrass seeds. For ZT wheat, rice residue mulch (6 to 10 t ha^{-1}) in combination with early sowing reduced emergence of littleseed canarygrass by over 80%. Other promising nonchemical approaches that can be useful in suppressing weeds in ZT RW systems include use of certified seeds, weed-competitive cultivars, stale seedbed practices, living mulches (e.g., sesbania coculture), and water and nutrient management practices that shift weed–crop competition in favor of the crop. However, more research on emergence characteristics and mulching effects of different crop residues on key weeds under ZT, cover cropping, and breeding crops for weed suppression will strengthen nonchemical weed management programs. Efforts are needed to integrate multiple tactics and to evaluate long-term effects of nonchemical weed management practices on RW cropping system sustainability.

Nomenclature: Barnyardgrass, *Echinochloa crus-galli* (L.) Beauv.; littleseed canarygrass, *Phalaris minor* Retz.; sesbania, *Sesbania rostrata* Brem. & Oberm.; rice, *Oryza sativa* L.; wheat, *Triticum aestivum* L.

Key words: Crop geometry, crop rotation, nonchemical approaches, planting dates, residue mulch, seed rate, sesbania coculture, stale seedbed, weed competitive cultivars, weed seedbank.

En sistemas de arroz-trigo (RW) de las planicies Indo-Gangéticas del sur de Asia, se está promoviendo el uso de prácticas de labranza de conservación, incluyendo labranza cero (ZT), para solucionar problemas emergentes tales como (1) escasez de agua y mano de obra, (2) reducción de productividad, (3) deterioro en la salud del suelo, y (4) cambio climático. A pesar de los múltiples beneficios de ZT, el control de malezas continúa siendo uno de los mayores retos para la adopción de esta tecnología, lo que resulta en una mayor dependencia en herbicidas para el control de malezas. Se necesitan estrategias alternativas de manejo para reducir la dependencia en herbicidas y minimizar los riesgos asociados a su sobreuso, incluyendo la evolución de resistencia a herbicidas. Los objetivos de esta revisión son (1) resumir y resaltar los esfuerzos de investigación en el manejo no-químico de malezas en sistemas ZT RW e (2) identificar las necesidades futuras de investigación sobre ecología y manejo de malezas para facilitar el éxito en la adopción de estos sistemas. En sistemas ZT RW, el residuo del cultivo puede jugar un rol central en la supresión de malezas mediante efectos de cobertura sobre la emergencia y la depredación de semillas. En arroz ZT, la cobertura con residuos de trigo (5 t ha^{-1}) redujo la densidad de malezas 22 a 76% y promovió la depredación de malezas de RW, incluyendo semillas de *Phalaris minor* y *Echinochloa crus-galli*. Para trigo RW, la cobertura con residuos de trigo (6 a 10 t ha^{-1}) en combinación con siembra temprana redujo la emergencia de *P. minor* en más de 80%. Otras estrategias no-químicas promisorias que pueden ser útiles para suprimir malezas en sistemas ZT RW incluyen el uso de semilla certificada, el uso de cultivares competitivos contra las malezas, y prácticas de siembra retrasada, coberturas vivas (e.g. *Sesbania rostrata* como co-cultivo), prácticas de manejo de agua y nutrientes que cambien la relación de competencia maleza-cultivo en favor del cultivo. Sin embargo, más investigación sobre características de emergencia y efectos de diferentes residuos de cultivos como coberturas sobre especies clave en ZT, coberturas vivas y mejoramiento genético de los cultivos para supresión de malezas fortalecerá los programas de manejo no-químico de malezas. Se necesitan esfuerzos para integrar múltiples tácticas y para evaluar los efectos en el largo plazo de las prácticas no-químicas de manejo de malezas sobre la sostenibilidad de sistemas de cultivos RW.

Rice–wheat (RW) cropping systems occupy 10.3 million ha of the Indo-Gangetic Plains (IGP) in India and are crucial for the food security in the region. The IGP accounts for 23% of India's rice area and 40% of its wheat area and contributes a major share of total cereal production (Timsina and Connor 2001). Recently, the sustainability of this cropping system is at risk because of stagnant or declining productivity growth of both rice and wheat and declining total factor productivity

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(measure of grain output divided by the quantity all input taken together; Ladha et al. 2009). This could be attributed to multiple factors, including (1) degradation in the natural resource base, especially soil and water; (2) rising scarcity of labor and water; (3) increasing costs of cultivation; and (4) increasing weed abundance and evolution of herbicide resistance in littleseed canarygrass, a major weed of wheat (Ladha et al. 2003, 2009; Malik and Singh 1995).

In the RW system, rice is grown during the summer rainy season from June to October and wheat during the winter dry season from November to April. Rice is primarily grown by conventional puddled transplanting (CT-TPR), in which approximately 1-mo-old rice seedlings are transplanted manually into puddled soil (wet tillage) and fields are kept flooded. This practice of rice production is effective in (1) achieving good weed control and crop establishment, (2) reducing percolation losses of water and nutrients, and (3) enhancing nutrient availability (Johnson and Mortimer 2005; Sanchez 1973; Sharma et al. 2003). However, CT-TPR is labor intensive, requires large amounts of water, and is detrimental to soil health (Gathala et al. 2011; Kumar and Ladha 2011). As a result, alternative practices, including dry direct-seeding (DSR) with reduced or zero-tillage (ZT) are being explored. ZT-DSR can reduce water and labor requirements and eliminate the adverse effects of puddling on soil health and on the productivity of the succeeding wheat crop (Gupta and Seth 2007; Kumar and Ladha 2011; Ladha et al. 2009). Additionally, ZT in wheat reduces the time required to prepare the soil for wheat, resulting in more timely planting and higher yields. Tripathi et al. (2005) estimate that each 1-d delay of wheat planting past the optimal date results in a yield loss of 26.8 kg ha^{-1} d^{-1}.

In wheat, ZT has been widely adopted, especially in the northwestern IGP in the RW systems, and has positive effects on wheat productivity, profitability, and resource use efficiency (Chhokar et al. 2007; Erenstein and Laxmi 2008, Gupta and Seth 2007; Ladha et al. 2009; Malik et al. 2002). However, the full benefits of ZT have not been realized in RW systems because rice is still mostly grown by the CT-TPR method. Therefore, recent efforts have focused on development and promotion of ZT in rice, either by DSR or mechanical transplanting in unpuddled ZT conditions (Kumar and Ladha 2011; Malik and Yadav 2008).

Despite multiple benefits of ZT in RW systems, weed control remains a major obstacle to its adoption. Weed control is particularly challenging in ZT-DSR because of the diversity and severity of weeds and because ZT-DSR is typically associated with a shift away from transplanting and flooding, both of which play an important role in suppressing weeds under CT-TPR. Yield losses because of weeds have been reported to be much higher in ZT-DSR compared with CT-TPR (Kumar and Ladha 2011; Kumar et al. 2008; Rao et al. 2007; Singh et al. 2011). Similarly, in wheat, losses because of weeds are reported higher in ZT compared with CT. Under ZT wheat, emergence and biomass of littleseed canarygrass was reduced, but weed flora shifted toward more broadleaf weeds compared with conventional tillage (CT) (Chhokar et al. 2007, 2009).

Herbicide use has increased in both CT and ZT systems because it provides effective and economical weed control and saves on labor, which has become more scarce and expensive (Rao et al. 2007). Although herbicides play an important role in facilitating adoption of ZT practices, overreliance has exacerbated problems of herbicide resistance in weeds (CAST 2012; Heap, 2012). Additionally, public concerns about the potential adverse effect of herbicides on neighboring water resources (Guzzella et al. 2006; Spalding et al. 2003) and human health (USEPA 2007; Pingali and Marquez 1996) have increased.

Herbicide resistance is a major problem in wheat and could become a problem in rice with adoption of ZT. In wheat, sole dependence on POST-applied herbicides for weed control has resulted in the evolution of multiple herbicide resistance in littleseed canarygrass, the single most important weed of wheat (Chhokar and Sharma 2008; Malik and Singh 1995). In rice, no cases of herbicide resistance have appeared yet in the IGP. Lack of herbicide resistance development in rice could be due in part to integration of multiple tactics for weed control in CT-TPR, including puddling, transplanting, and continuous flooding practices. Additionally, preemergence herbicides (butachlor, pendimethalin, and pretilachlor) used in rice are relatively less prone to resistance evolution than herbicides used in wheat. However, the adoption of direct seeding in rice might result in increased reliance on POST-applied herbicides to compensate for the loss of weed suppression from tillage, flooding, and transplanting. Most of the commonly used POST herbicides for weed control in DSR in the IGP are either acetolactate synthase or acetyl-CoA carboxylase inhibitors (Kumar and Ladha 2011), which are more prone to evolution of resistance (HRAC 2012).

To expand the adoption of ZT in RW systems while minimizing the risks associated with herbicide use, it is important to develop alternative nonchemical weed management packages. Nonchemical management of weeds under ZT is challenging because both tillage and herbicides, two major weed control methods, are removed from the systems. However, integration of multiple tactics, including the use of stale seedbed, crop residue as mulch, competitive cultivars, crop rotation, and manipulation of sowing time and plant density, have been reported effective in suppressing weeds and can be included as part of an alternative weed management program (Kumar and Ladha 2011; Singh 2007).

The objectives of this paper are to review (1) key weed species of rice and wheat crops under ZT conditions, (2) effectiveness of different alternative weed management approaches in ZT rice–wheat systems of the IGP, and (3) identify future research needs to further strengthen nonchemical weed management programs.

Key Weed Species of Rice and Wheat under ZT

Knowledge of the ecology and biology of weeds can help in developing targeted weed management tactics. With the shift from CT to ZT, soil disturbance is reduced drastically and soil surface is often covered with previous crop residues. Tillage can influence the vertical weed seed distribution in the soil profile, soil moisture, diurnal temperature fluctuations, light availability, and activities of seed predators and microbes. All these factors can affect weed recruitment in the field by influencing seed dormancy, emergence, and seed mortality (Mohler 1993). Effects of some of these factors on key weed species of zero-till rice and wheat are discussed in this section.

Rice Weed Species. The shift from CT-TPR to DSR with reduced or ZT, typically results in changes in tillage, crop establishment method, irrigation practices, and weed management that influence weed diversity and abundance. Under ZT-DSR, weed flora often shifts towards more difficult-to-control and competitive grasses and sedges (Kumar and Ladha 2011). Based on experiences with ZT-DSR in India and other Asian countries, the shift from CT-TPR to ZT-DSR is expected to favor grass weed species including crowfootgrass (*Dactyloctenium aegyptium* Willd.), chinese sprangletop [*Leptochloa chinensis* (L.) Nees], love grass [*Eragrostis* spp., including *japonica* (Thunb.) Trin.], and weedy rice (*Oryza sativa* L.), along with barnyardgrass and junglerice [*E. colona* (L.) Link.]; sedges such as globe fringerush [*Fimbristylis miliacea* (L.) Vahl], purple nutsedge (*Cyperus rotundus* L.), and rice flatsedge (*Cyperus iria* L.) would dominate under DSR systems (Kumar and Ladha 2011). Other important weeds of rice under ZT in RW systems include broadleaves such as eclipta [*Eclipta prostrata* (L.) L.], red stem (*Ammannia* spp.), Caesulia (*Caesulia axillaris* Roxb.), gooseweed (S*phenochloa zeylinica* Gaertn.), horsepurslane (*Trianthema portulacastrum* L.), niruri (*Phyllanthus niruri* L.), and *Digera arvensis* Forssk. and sedges such as smallflower umbrella sedge (*Cyperus difformis* L.).

The ecology and biology of eight of these key weed species are summarized in Table 1. Most are able to germinate over a wide range of temperatures but prefer moist and warm conditions (Table 1). These traits make these species adapted to rice conditions. Germination of smallflower umbrella sedge and Chinese sprangletop has been found to be more sensitive to water stress than in other species (Table 1). For example, water potential of about –0.11 MPa was required to inhibit 50% germination of smallflower umbrella sedge and Chinese sprangletop, whereas for other species, a water potential of –0.46 to –0.80 MPa was needed (Table 1; Chauhan 2011; Chauhan and Johnson 2008a,b, 2009a,b, 2011a).

Most key rice weeds form a relatively persistent seedbank (Table 1), although estimates vary widely for many species. For example, the time required for more than 95% of barnyardgrass seeds to loose viability varied from 2.5 to 13 yr (Table 1; Dawson and Bruns 1975; Egley and Chandler 1978; Maun and Barrett 1986). However, no seed was found viable after 15 yr (Dawson and Bruns 1975). In the case of junglerice, 1.4% of seeds remained viable after 7 yr (Table 1; Uremis and Uygur 2005). Seed longevity of crowfootgrass has been reported to be greater than 6 yr. More than 54% of crowfootgrass seeds remained viable, even after 6 yr. Similarly, smallflower umbrella sedge seeds have been reported to survive up to 6 yr in the soil (Table 1; Sanders 1994).

Seed germination of many of the key rice weed species is stimulated by light (Table 1). Species like smallflower umbrella sedge, rice flatsedge, and globe fringerush require light to germinate (Chauhan and Johnson 2009a). Other species, including barnyardgrass, junglerice, and crowfootgrass, do not have an absolute light requirement for germination but are stimulated to germinate more by light (Chauhan 2011; Chauhan and Johnson 2009b, 2011). Chinese sprangletop populations have variable responses to light; populations from the Philippines did not germinate in dark (Chauhan and Johnson 2008a), but the Italian population did (Benvenuti et al. 2004).

Emergence of most key weed species of ZT rice is very sensitive to seed burial depth (Table 1). Maximum emergence generally occurs for seeds at or near the soil surface. Emergence of most annual sedges is highly inhibited when their seeds are placed at depths of > 0.5 cm and totally inhibited from depths greater than 1 cm (Table 1; Chauhan and Johnson 2009a). Similarly, emergence of eclipta (a broadleaf weed) was completely inhibited at burial depths of ≥ 0.5 cm (Table 1; Chauhan and Johnson 2008b). For junglerice and crowfootgrass, maximum emergence depth is 6 cm, whereas barnyardgrass can emerge from depths up to 10 cm (Table 1; Chauhan 2011; Chauhan and Johnson 2009b, 2011a).

The response to light, seed burial depth, and low dormancy helps explain why the eight key weed species discussed in Table 1 are dominant in ZT systems. These species are well adapted to conditions at the soil surface, where weed seeds in ZT systems typically concentrate (Chauhan and Johnson 2009b).

Wheat Weed Species. The predominant weeds associated with wheat under RW system are littleseed canarygrass, annual bluegrass (*Poa annua* L.), foxtail grass (*Polypogon monspeliensis* Desf.), wild oat (*Avena ludoviciana* Durieu), Indian sorrel or toothed dock (*Rumex dentatus* L.), pimpernel (*Anagallis arvensis* L.), field bindweed (*Convolvulus arvensis* L.), little mallow (*Malva parviflora* L.), bur clover (*Medicago denticulata* Willd), common lambsquarters (*Chenopodium album* L.), common vetch (*Vicia sativa* L.), meadow pea (*Lathyrus aphaca* L.), Canada thistle (*Circium arvense* L.), white sweet clover (*Melilotus alba* Lamk), swine grass (*Coronopus didymus* L.), alpine knotweed (*Polygonum plebejum* R. Br.), purple nutsedge (*Cyperus rotundus* L.), bermudagrass (*Cynodon dactylon* L. Pers.), and corn spurry (*Spergula arvensis* L.).

Among these weeds, littleseed canarygrass is the single most important grassy weed of wheat. This weed is highly competitive, causing significant yield reductions in the range of 25 to 80% depending on the severity of infestation (Chhokar and Malik 2002; Franke et al. 2003; Singh et al. 1999). This species has evolved resistance (Chhokar and Malik 2002; Chhokar and Sharma 2008; Malik and Singh 1993) to multiple herbicides, especially in the northwest IGP and, as a result, has greatly limited wheat productivity. The ability of this weed to survive the anaerobic conditions in rice has made it fit for the RW system (Chhokar 1998). In contrast, the sensitivity of wild oat to prolonged water stagnation in rice is responsible for its elimination from the RW system, except in very light soils (Chhokar, unpublished data).

The shift from CT to ZT in wheat has resulted in a shift in weed flora. Emergence of littleseed canarygrass is lower under ZT than CT in wheat (Chhokar et al. 2007; Franke et al.

Table 1. Seed germination and emergence responses of eight key weed species of rice observed under zero-till conditions.[a,b]

Factors	Barnyardgrass	Junglerice	Crowfootgrass	Chinese sprangletop	Eclipta	Smallflower umbrella sedge	Rice flatsedge	Globe fringerush
Temperature	Germinate over wide range of temperatures from 13 to 40 C	Similar germination over wider range of temperature	Can germinate over wider range: 15–35 C	Higher temperature favors germination. More germination at 30/20 C to 35/25 C than at 25/15 C	Germination at 25/15, 30/20, 35/25 C was 76–93%	Higher germination at warmer temperatures (30/20 C and 35/25 C day/night) than at cooler temperature (25/15 C)	Greater germination at warmer temperatures (30/20 C and 35/25 C day/night) than at cooler temperature (25/15 C)	Greater germination at warmer temperatures (30/20 C and 35/25 C day/night) than at cooler temperature (25/15 C)
Light	Not absolute requirement, but germination is stimulated by light	Not absolute requirement, but germination is stimulated by light	Not absolute requirement, but germination is stimulated by light	Polymorphic to light. In Philippines population, no germination in dark, but in Italian population, only 20% germination in dark compared with under light	No germination in dark, and germination is stimulated by light	No germination in dark, and germination is stimulated by light	No germination in dark, and germination is stimulated by light	No germination in dark, and germination is stimulated by light
Dormancy	Present	Present but lower than barnyardgrass	Present	Present in Indian population but not found in Philippines population	Absent	Absent	Present	Absent
Seed longevity	Variable. Time to lose seed viability > 99% ranged from 2.5 to 13 yr. No seeds found viable after15 yr	Of seeds, 1.4% remained viable after 7 yr of burial	Longer than 6 yr. After 6 yr 54% seeds remained viable	Unknown	Unknown	90% of seeds remained viable after 6 yr of dry storage and survived up to 5–6 years in soil in fallow period	Unknown	Unknown
Water/soil moisture stress	Best germination at 70–90% field capacity	Germination favored by moist environment and decreased from 80 to 1% as osmotic potential decreased from 0.0 to −0.8 MPa and completely inhibited at −1.0 MPa. Osmotic potential required to reduce 50% germination to that of maximum was −0.46 MPa	Germination favored by moist environment; decreased from 90 to 9% as osmotic potential decreased from 0.0 to −0.6 MPa and completely inhibited at −0.8 MPa	Germination decreased from 93 to 0% with decrease in osmotic potential from 0.0 to −0.4 MPa. Osmotic potential required to reduce 50% germination to that of maximum was −0.11 MPa	Germination favored by moist environment. Germination decreased from 94 to 2% with decrease in osmotic potential from 0.0 to −0.8 MPa. Complete inhibition at −1.0 MPa. Osmotic potential required to reduce 50% germination to that of maximum was −0.58 MPa	Less germination under aerobic conditions than under saturated conditions (55 vs. 23%). Germination is more sensitive to moisture stress than other two sedge species. Osmotic potential required to reduce 50% germination to that of maximum was −0.12 MPa	Similar germination in saturated and aerobic conditions. Osmotic potential required to reduce 50% germination to that of maximum was −0.46 MPa	Similar germination in saturated and aerobic conditions. Osmotic potential required to reduce 50% germination to that of maximum was −0.69 MPa
Seed burial depth	Emergence occurred from seed burial depths of 0–10 cm, with maximum between 1 and 2 cm depth, then it declined. No emergence from seeds beyond 10 cm depth	The highest emergence from surface-seeded seeds (97%), decreased with increase in seeding depth (76% at 0.2 cm and 12% at 0.5 cm). No emergence from 6 cm depth	Maximum emergence from surface-seeded seeds (64%); decreased with increase in depth (51% at 0.5 cm). Emergence reduced by 84% at 4 cm depth and completely inhibited at 6 to 8 cm depths	Polymorphic to burial depth. In Philippines population, maximum emergence from surface-seeded seeds and no emergence from 0.5 cm depth, but from Indian and Italian population, it emerged from 5 cm depth, also, with maximum from 0 and 2.5 cm depths	Maximum emergence from surface- seeded seeds. Emergence decreased by 75% at 0.2 cm compared with surface seeding and completely inhibited at 0.5 cm depth	The highest emergence from seeds placed on soil surface, and it decreased with increase in seed burial depths. No emergence from ≥ 1 cm depth. Emergence suppressed > 95% at 0.5 cm depth	Response similar to smallflower umbrella sedge	Maximum emergence from surface-seeded seeds and complete inhibition at ≥ 0.5 cm soil depth

Table 1. Continued.

Factors	Barnyardgrass	Junglerice	Crowfootgrass	Chinese sprangletop	Eclipta	Smallflower umbrella sedge	Rice flatsedge	Globe fringerush
Tillage favored	Zero-tillage	Zero-tillage	Zero-tillage	Zero-tillage	Zero-tillage	Zero-tillage	Zero-tillage	Zero-tillage
Residue mulch	Rice residue mulch did not affect emergence up to 2 t ha^{-1} and growth up to 4 t ha^{-1}. However, 6 t ha^{-1} residue reduced emergence and growth by 55%	Rice residue of 1–2 t ha^{-1} and 4–6 t ha^{-1} suppressed emergence by 32–55% and 78–90%, respectively, compared with no residue control	Emergence was 35% lower with 1 t ha^{-1} residues; 82 to 92% lower with 4 to 6 t ha^{-1} residues compared to without residue control	Unknown	Emergence not affected by 1 t ha^{-1} rice residues but reduced by > 90% at 6t ha^{-1}	Unknown	Unknown	Unknown
Flooding	Flooding of 4 cm reduced emergence. Established plant not killed with flooding. Early flooding (5 DAS) reduced growth (e.g., 2 cm flooding reduced growth by 22% and 10 cm flooding 68% compared with saturated conditions). No effect on growth of 2-cm flooding 10 DAS. Flooding did not affect growth applied 15–20 DAS	Flooding to a depth of 4 cm reduced emergence	Flooding of 2.5 cm water completely inhibits germination and emergence	No seedling emerged from continuous flooding of ≥ 5 cm depth. Under submergence of 2.5 cm depth, only 30% seedlings compared with moist soil were able to emerge from soil but failed to emerge from water surface. Although seedlings failed to emerge under continuous flooding, after termination of flooding, some seedlings were able to emerge	Growth reduced if deep flooding (10 cm) at or before four-leaf stage	Shallow intermittent flooding did not reduce emergence but deep flooding of 10 cm reduced > 90% emergence. However, continuous flooding of 4 cm completely inhibited growth and emergence. Flooding at early stage (7–14 DAS) was effective in suppressing growth but was ineffective at later stage (21 DAS)	Shallow intermittent flooding reduced emergence by 45%, which increased to 94% with continuous flooding. Continuous flooding > 2 cm completely inhibited emergence and growth. Flooding at 7 DAS reduced growth by 94%, but less effective at later stage (21 DAS)	More sensitive to flooding than rice flatsedge and smallflower umbrella sedge. Intermittent flooding at shallow depth (2 cm for 4 of 7 d) reduced emergence by 94%, which increased to 100% inhibition with continuous shallow flooding of 3–4 cm

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[a] Sources: Benvenuti et al. (2004); Chauhan and Johnson (2008a,b, 2009a,b); Dawson and Bruns (1975); Egley and Chandler (1978); Lee and Moody (1988); Maun and Barrett (1986); Saeed and Sabir (1993); Sanders (1994); Uremis and Uygur (2005).

[b] Abbreviation: DAS, days after sowing.

2007; Gupta and Seth 2007; Malik et al. 2002) but higher for some of the broadleaf weeds, such as Indian sorrel (Chhokar et al. 2007). Lower littleseed canarygrass emergence under ZT is unlikely due to differences in the vertical distribution of seeds in soil under the two tillage systems because seeds are thoroughly mixed during puddling operations done in the rice season (Franke et al. 2007). The lower emergence of littleseed canarygrass under ZT may be attributed to (1) higher soil strength in ZT because of crust development in the absence of tillage after rice harvest, which can mechanically impede seedling emergence (Chhokar et al. 2007), and (2) higher weed seed predation under ZT (Kumar et al., unpublished data). Other possible factors could be (1) less soil temperature fluctuation because ZT helps in moderating soil temperature (Gathala et al. 2011) or (2) lower levels of light stimuli, N mineralization, or gas exchange, all of which are known to stimulate germination of many weed species following tillage (Franke et al. 2007).

The higher population of Indian sorrel under ZT wheat following CT-TPR may be due to a higher concentration of their seeds on the soil surface (Chhokar et al. 2007, 2009). It has been observed that after puddling operations in rice, seeds of Indian sorrel float (because seeds are light and have a perianth) and accumulate on the soil surface, where they can remain in a ZT wheat system; in contrast, under CT wheat, emergence is reduced because seeds are buried during tillage operations. Seeds of this species are sensitive to burial depth, and seeds buried at a depth $\geq$ 4 cm could not emerge (Dhawan 2005). Indian sorrel, besides reducing grain yield and quality of wheat, can also cause hinder combine harvesting under heavy infestation.

If ZT is adopted in both rice and wheat, then there are chances of a shift in weed flora toward perennial weeds like burmudagrass. In the Eastern IGP, problems with perennials such as purple nutsedge and bermudagrass are serious under ZT because tillage is not used to disrupt perrenation and because of inadequate/poor crop canopy to out-compete these weeds as a result of lower N use and late planting of the crop in the region (R.K. Malik, personal communication). Moreover, poor management of perennial weeds before seeding crops under ZT also leads to a continuous build-up of stored food in the underground parts of perennial weeds.

The ecology and biology of key wheat weed species are discussed in Table 2. Most of the wheat weed species are able to germinate over a wide range of temperature, but 10 to 20 C or 10 to 25 C has been found to be optimum for their germination (Table 2). Although light is not an absolute requirement for germination of major wheat weeds, their germination is stimulated by light. Littleseed canarygrass and Indian sorrel have been found to be more sensitive to moisture stress than other species such as white sweet clover, and their germination was completely inhibited at an osmotic potential of –0.8 and –0.5 MPa, respectively. White sweet clover germination was not affected by a decrease in osmotic potential from 0.0 to –0.8 MPa, and as a result, this weed is found both in irrigated and rainfed environments. Germination of wheat is less sensitive to moisture stress compared with littleseed canarygrass and Indian sorrel, major grass and broadleaf weeds of wheat, as even at an osmotic potential of –1.0 MPa, 55% seeds of wheat were able to germinate.

Almost no information is available on weed seed longevity of wheat weed seeds in soil except littleseed canarygrass (Table 2). Seeds of littleseed canarygrass remain viable longer in laboratory conditions than in soil. The longevity of this weed seed was found to be $<$ 2 yr in RW systems and $<$ 1 yr in cotton–wheat systems, suggesting that crop rotation can be an effective strategy to manage this troublesome weed. The response of weed emergence to seeding depth is variable, but maximum emergence has been found when seeds are near the soil surface. Indian sorrel was found to be most sensitive to seeding depth, and emergence was completely inhibited beyond seeding depths of 4 cm, whereas other species were able to germinate from seeding depths of 8 to 10 cm.

Nonchemical Weed Management Approaches for Weed Control in Zero-Till Rice–Wheat Systems

Zero-Tillage Rice. *Stale Seedbed.* In the stale seedbed technique, weed seeds are encouraged to germinate and then are killed by either a nonselective herbicide (paraquat, glyphosate, or glufosinate) or by shallow tillage before sowing of rice. This method has great potential for suppressing weeds and is feasible under ZT-DSR because there is about a 45- to 60-d fallow period between wheat harvest and sowing of rice. This technique is effective not only in reducing weed emergence during the crop season but also in reducing the weed seedbank (Kumar and Ladha 2011; Rao et al. 2007; Singh et al. 2009). Small-seeded weed species such as rice flatsedge, smallflower umbrella sedge, globe fringerush, eclipta, and Chinese sprangletop have low seed dormancy and are not able to emerge from depths $>$ 1 cm (Table 1). Therefore, the seedbank of these species can be exhausted relatively quickly under ZT before rice sowing using nonselective preseeding herbicides. Renu et al. (2000) reported that the stale seedbed technique is more effective under ZT, in which weeds are killed without disturbing the soil but by using nonselective herbicides, than with mechanical methods (e.g., tillage), which bring seeds back into the germination zone.

However, very few studies have quantified the effects of stale seedbeds on weed suppression in DSR. In a field study conducted at Karnal, India, in 2005 and 2006, a stale seedbed using presowing irrigation once in combination with herbicide application reduced the weed density of grasses (44 to 56%), broadleaf weeds (58%), and sedges (56 to 68%), resulting in 60% lower weed biomass compared with standard practices (Table 3). When stale seedbeds were used with two pre-sowing irrigations, weed density decreased by 77 to 85% and weed biomass by $>$ 85%. When stale seedbed was supplemented with hand weeding, weed control was further improved, resulting in weed density reductions of 74 to 90% and 92 to 97% and weed biomass by 85 to 88% and 97% in stale seedbed treatments with one and two presowing irrigations, respectively.

On the basis of farmer field trials, Singh et al. (2009) also observed a 53% lower weed population after stale seedbed practices in DSR. With the limited options available to

Table 2. Seed germination and emergence responses of major weeds of zero-tillage wheat.[a]

Factors	Littleseed canarygrass	Indian sorrel	White sweet clover	Meadow pea	Field bindweed	Little mallow
Temperature	Germinate over a range of temperatures from 10 to 25 C, but optimum at 10 to 20 C	Can germinate over temperature range or 10–20C	—	Can germinate over a wider range of 5–35C, optimum being 10–25 C	Can germinate over a wider range of 5–35 C, optimum being 10–25 C	—
Light	Not absolute requirement but germination is stimulated by light	Not absolute requirement, but germination is stimulated by light	—	Not required for germination	Not required for germination	Insensitive to light
Seed longevity	In field, < 2 yr in rice–wheat system and < 1 year in cotton–wheat system. In laboratory, time to lose seed viability about 95% is 6 yr	—	Laboratory-stored seeds remain viable ≤ 8 yr	—	—	—
Water stress/ soil moisture	Germination decreased from 99 to 0% with decrease in osmotic potential from 0 to -8 bars, whereas wheat seed germination was 55%, even at -10 bar osmotic potential	Germination favored by moist environment, and germination completely inhibited at osmotic potential > 0.5 MPa	Germination and seedling growth is not affected with decrease in osmotic potential from 0.0 to -0.8 MPa. As a result, it is found infesting wheat in irrigated as well as rainfed areas	—	—	—
Seed burial depth	Emergence occurred from seed burial depths of 0–10 cm, with maximum up to 2.5 cm depth, then it declined. No emergence from seeds > 10 cm depth	Highest emergence from 0 to 1 cm seeding depth, and no seedling emerged > 4 cm seeding depth	Maximum emergence from surface-seeded seeds and emergence declined with increased seeding depth, with no emergence from a seeding depth of ≥ 8 cm	Highest emergence from seeds placed 1 cm below soil surface, and can germinate from soil depth ≤ 8 cm	Highest emergence from seeds placed 1 cm below soil surface, and can germinate from soil depth ≤ 8 cm	Maximum emergence from 0.5–2.0 cm; seeding depth beyond decreased its emergence, and no emergence from a depth > 8 cm
Tillage favored	Conventional tillage	Zero-tillage	Zero-tillage	—	—	Zero-tillage
Residue mulch	Rice residue burning stimulates its emergence, but residue retention ≥ 5 t ha^{-1} significantly reduces its emergence	Residue mulch 4 t ha^{-1} or more inhibits its emergence	Residue mulch > 4 t ha^{-1} reduced its emergence	—	—	—

[a] Sources: Chhokar (1998); Dhawan (2005, 2009); Singh and Punia (2009).

Table 3. Effects of stale seedbed technique and hand weeding on weed density and weed dry weight 60 d after sowing (DAS) and on grain yield[a,b] in 2005 and 2006 (Source: Samar Singh, unpublished data).[c]

	Grasses		Broadleaves		Sedges		Weed DW		Yield	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
	No. m^{-2}						g m^{-2}		kg ha^{-1}	
No stale seedbed	78	54	52	68	44	50	205	185	386	540
Stale seedbed with one irrigation	34	30	22	28	14	22	83	70	1,442	1,684
Stale seedbed with two irrigations	18	12	8	12	8	11	29	25	2,256	2,620
No stale seedbed + HW	24	18	12	14	26	24	52	39	1,628	2,236
Stale seedbed with one irrigation + HW	12	14	8	7	5	8	31	23	2,144	2,638
Stale seedbed with two irrigations + HW	4	3	2	2	3	4	7	5	2,621	2,930
LSD at 5%	12	7	5	9	8	5	21	19	240	305

[a] Variety: CSR-30 (basmati-type); seed rate: 35 kg ha^{-1}.

[b] Date of seeding: June10, 2005, and June 16, 2006. Date of harvesting: November 5, 2005, and November 8, 2006.

[c] Abbreviations: HW, hand weeding; LSD, least significant difference; DW, dry weight.

manage weedy rice in ZT-DSR, the stale seedbed technique is recommended as part of an integrated weed management strategy in many weedy rice-infested areas (Delouche et al. 2007; Rao et al. 2007).

Crop Establishment Methods. Zero-till rice can be established either by direct seeding (ZT-DSR) or by transplanting (ZT-TPR) rice seedlings manually or mechanically (using a paddy transplanter). Under DSR, weeds are more diverse and difficult to control compared with TPR (Chhokar et al., unpublished; Kumar and Ladha 2011; Rao et al. 2007; Singh et al. 2011). Chhokar et al. (unpublished), observed that, in the absence of weed control measures, yield losses due to weeds were $> 90\%$ under ZT-DSR, compared with 35 to 42% under ZT-TPR.

When rice is transplanted, the initial flush of weeds can be managed by flooding, which is not possible under DSR. Moreover, transplanting gives rice a competitive advantage because of the initial size differential between transplanted rice and weeds. Chhokar et al. (unpublished) found $> 80\%$ lower weed biomass of junglerice and Chinese sprangletop in ZT-TPR compared with ZT-DSR. Where DSR is preferred for saving labor and water resources, ZT-DSR can be rotated with ZT transplanted rice every few years to keep weed pressure under check.

Seed Rate and Crop Geometry. Weed competition in ZT-DSR can also be reduced by optimizing seed rate and the crop geometry (Chauhan 2012). In a study conducted in India and the Philippines, it was found that weed biomass declined linearly with an increase in seed rate and about 40 to 59% lower weed biomass was observed with an increase in seeding rate from 25 to 100 kg ha^{-1} (Chauhan et al. 2011). Similarly, in another study conducted in Malaysia, weed density and biomass were reduced by 22 to 25% when seeding rate was increased from 200 to 300 seeds m^{-2} and by 42 to 45% when seeding rates were increased to 400 seeds m^{-2} (Anwar et al. 2011).

Most seed rate studies report increases in rice grain yields with increases in seed rate under weedy conditions only, and not in weed-free conditions (Anwar et al., 2011; Castin and Moody 1989; Chauhan et al. 2011; Guyer and Quadranti 1985). Under weed-free conditions, yields were not affected by seeding rates ranging from 15 to 125 kg ha^{-1} (Chauhan et al. 2011; Zhao et al. 2007). However, under weedy conditions, weed biomass decreased linearly, and yields increased quadratically with increased seed rates (Chauhan et al. 2011). In the absence of weeds, optimal seeding rates are often lower because high seeding rates can cause N deficiency, higher spikelet sterility, fewer grains per panicle, higher incidence of insects and diseases, and crop lodging (Kumar and Ladha 2011).

In the IGP, a seed rate of 20 to 25 kg ha^{-1} has been recommended for DSR (Kumar and Ladha 2011) under optimum weed control. However, results of Chauhan et al. (2011) suggest that a seeding rate of 95 to 125 kg ha^{-1} for inbred varieties and 83 to 92 kg ha^{-1} for hybrid varieties is needed to achieve maximum yields in competition with weeds.

Crop geometry, including row spacing and planting pattern, can also influence crop–weed competition. Narrow row spacing can shift the competitive balance in favor of rice by achieving faster canopy closure and reducing light availability to weeds (Chauhan and Johnson 2011b). Reductions in row spacings from 45 to 15 cm had no effect on yields under wee-free conditions but increased yields where weeds were present (Akobundu and Ahissou 1985; Chauhan and Johnson. 2011b). Chauhan and Johnson (2011b) reported reductions in critical periods of weed control by 8 d with 15-cm row spacing compared with 30-cm row spacing. Weed competition can also be reduced for some cultivars by sowing rice in a paired-row pattern (Mahajan and Chauhan 2011). Weed biomass was 25% lower under paired-row sowing (15-30-15 cm) of rice cultivar 'PR 115' compared with uniform row spacing of 23 cm, but weed biomass was not affected by planting pattern for cultivar 'Punjab Mahak 1', a more competitive cultivar (Mahajan and Chauhan 2011). These results suggest that weed competition in ZT-DSR can be reduced by growing rice with narrow spacing or in a paired-row planting pattern. However, narrow row spacing could make other weed control operations, including hand weeding and mechanical weeding, more difficult compared with wide row spacing (Chauhan 2012).

Residue Mulching. Because many key species of ZT rice are sensitive to light and burial depth (Table 1), mulches might provide a useful method for suppression (Chauhan 2012; Singh et al. 2007). In a pot study, rice residue as mulch reduced the emergence and growth of barnyardgrass, junglerice, crowfootgrass, and eclipta (Table 1). For significant suppressive effects of mulch on emergence and growth of barnyardgrass and eclipta, 6 t ha^{-1} residue was needed, whereas, emergence of junglerice and crowfootgrass was reduced with as little as 1 to 2 t ha^{-1} .

ZT rice systems create opportunities for exploitation of surface residues for weed suppression that are not available when puddling and flooding are used. Because, most rice weed species are sensitive to mulching (Table 1), it can be an effective weed management strategy in ZT-DSR. Residue mulching suppresses weeds, reducing recruitment and early growth of weeds, by (1) imposing a physical barrier to emerging weeds (Mohler 1996; Mohler and Callaway 1991; Mohler and Teasdale 1993) and (2) releasing allelochemicals in the soil (Weston 1996). A few studies on residue mulches in rice have demonstrated substantial reduction in emergence and growth of weeds (Table 4; Chauhan 2012). In a study conducted in the Indian IGP in 2005 and 2006 (Table 4), it was found that wheat residue mulch of 5 t ha^{-1} reduced the emergence of grass, broadleaf, and sedge species in the range of 73 to 76%, 65 to 67%, and 22 to 70%, respectively, compared with no residue control in ZT-DSR. Because of lower weed density, total weed biomass was 70% lower, which resulted in $> 50\%$ higher grain yields. In ZT-DSR in the IGP, Singh et al. (2007) found that 4 t ha^{-1} wheat residue reduced emergence of grass and broadleaf weeds in the range of 44 to 47% and 56 to 72%, respectively.

Despite the significant positive effects of mulches on weed suppression, the limited availability of residue for mulch during the rice season is a constraint. In the IGP, previous

Table 4. Effects of wheat residue mulch and sesbania coculture on weed density and weed biomass 60 days after sowing (DAS) and grain yield[a,b] (Source: Samar Singh, unpublished data).[c]

	Grasses		Broadleaves		Sedges		Weed DW		Yield	
	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
	No. m^{-2}						g m^{-2}		kg ha^{-1}	
No residue	38	26	18	32	23	29	68.8	56.4	1,472	1,566
Full wheat residues	9	7	6	11	18	9	18.2	16.5	2,256	2,436
No residue + sesbania coculture	24	18	10	22	24	14	54.4	42.8	1,628	1,804
Full wheat residues + sesbania coculture	5	6	3	7	16	8	12.4	10.7	2,418	2,524
LSD at 5%	8	4	3	7	5	4	9.2	8.6	196	214

[a] Variety: CSR-30 (Basmati type); seed rate: 35 kg ha^{-1}.

[b] Date of seeding: June10, 2005, and June 16, 2006. Date of harvesting: November 5, 2005, and November 8, 2006.

[c] Abbreviations: LSD, least significant difference; DW, dry weight.

wheat crop residue is used as animal feed and hence removed from the field. Therefore, there is a need to identify alternative ways to generate residue mulch. One way is to grow short-duration additional crops such as mungbean [*Vigna radiate* (L.) R. Wilczek] during the fallow period between wheat harvest and rice planting and to retain the entire residue of this crop as mulch. Efforts are already underway to promote the adoption of mungbean during this fallow period to improve soil health.

Sesbania Coculture/Intercropping. Another approach that has shown promise for suppressing weeds in ZT rice production involves sowing sesbania at 25 kg ha^{-1} along with rice. Sesbania is allowed to grow with rice to suppress weeds and is then killed with 2,4-D ester 25 to 30 d after sowing (DAS). Singh et al. (2007) reported 76 to 83% lower broadleaf densities and 20 to 33% lower grass densities with this practice compared with only a rice crop. However, this practice may pose some risks, including (1) competition of sesbania with rice if 2,4-D application is ineffective or its application is delayed because of continuous rain, and (2) additional costs associated with sesbania seeds and management.

Competitive Cultivars. Currently, cultivars that were bred for CT-TPR are being used in ZT-DSR, and very limited efforts have been made to breed rice cultivars suitable for ZT-DSR, including weed competitiveness in the IGP (Kumar and Ladha 2011). However, several existing cultivars exhibiting weed competitiveness have been identified (Singh et al. 2009). Cultivars with early seedling vigor and spreading nature, which cover the ground quickly during the vegetative stage, result in the suppression of weeds (Kumar and Ladha 2011). In general, it has been observed that early maturing (short duration) inbred and hybrids are more effective in smothering weeds than medium- to long-duration cultivars because of their early faster growth and ground cover (Mahajan et al. 2011). Also, basmati (scented) varieties are more competitive against weeds than non-basmati varieties. In a study conducted at Modipuram, India, it was found that basmati or evolved basmati group cultivars suppressed weed growth 49% more than short-statured, high-yielding, coarse-grain cultivars (Singh et al. 2009). Mahajan and Chauhan (2011) also found that Punjab Mahak-1 (basmati-type with 125-d maturity) was superior in weed suppression to the coarse-grain cultivar PR 115 (non-basmati type with 125-d maturity). The higher competitive ability of basmati-type cultivars is attributed to early vigor, faster canopy cover, and taller nature of these varieties.

Water Management. Water management has been an important component of weed control in conventionally flooded CT-TPR, where flooding is established from the first day of transplanting. Emergence and growth of many rice weeds are influenced by timing, duration, and depth of flooding (Table 1). The emergence and growth of most weed species is inhibited only when fields are submerged shortly after seeding. In ZT-DSR, flooding cannot be applied immediately after sowing because rice seeds cannot germinate and survive under completely submerged conditions. Moreover, the duration of flooding is limited under ZT because infiltration rates are higher where soils are not puddled via tillage. Therefore, in DSR, many weeds can emerge before flooding is possible, making weed management difficult (Chauhan 2012).

The development of rice cultivars capable of germinating under anaerobic conditions would greatly facilitate weed management via flooding in DSR (Chauhan 2012). Work on development of rice cultivars capable of anaerobic germination is underway at the International Rice Research Institute (IRRI), Philippines. After screening > 8,000 varieties, IRRI has identified anaerobic germination traits in a few traditional varieties, such as Khaiyan from Bangladesh, Khao Hlan On from Myanmar, and Mazhan Red from China (IRRI 2011). This trait would not only help in weed control but also in enhancing the adoption of DSR in both rainfed and irrigated areas because crop establishment will be improved with this trait if untimely rain comes soon after sowing.

Strategies to Minimize Weed Seed Inputs. One way to deplete the seedbank is to minimize weed seed production. Even after practicing weed control, some weeds escape and can produce a large number of persistent seeds, which can further reduce yields or increase weed management costs in subsequent seasons. Attention should also be given to preventing seed production from weeds growing during the fallow period (between wheat harvesting and rice seeding) and on bunds and channels because they can contribute significantly to the soil seedbank.

Table 5. Effect of different level of residue mulch on emergence of four major weeds of wheat 45 d after sowing.[a]

Residue level	Littleseed canarygrass	Lambsquarter	Indian sorrel	Yellow sweet clover
	plants per 2-m row length			
0	185 a	238 a	42 a	14.0 a
4	142 ab	52 b	9 a	2.0 ab
6	101 bc	40 bc	5 b	2.0 ab
8	60 c	18 bc	2 b	0.3 b
10	80 c	2 c	0.3 b	0.3 b

[a] Within column, means with same letter are not significantly different at 0.05 level using Fischer's Protected LSD test.

Weed seeds could also gain entry into rice fields via contaminated owner-saved seeds, manures or compost, and irrigation water. These sources should be prevented by using certified seeds and well-decomposed and good-quality manures/compost free from weed seeds. Kelly and Bruns (1975) estimated dissemination of weed seed via irrigation water in the United States and found in the range of 10,400 to 94,500 seeds ha^{-1}. Therefore, screening of irrigation water should be included as part of effective weed control programs in canal-irrigated areas, and preventive measures should be developed to minimize weed seed dispersal via irrigation water.

Strategies to Maximize Weed Seed Depletion. Another approach to depleting weed seedbanks involves enhancing weed seed predation and decay. ZT with crop residues could enhance weed seed predation and seed decay because (1) in ZT a greater proportion of weed seeds remain on the soil surface where they are more prone to seed predation (Hulme 1994), (2) residues might provide a desirable habitat for seed predators and decay agents (House and Brust 1989; Doran 1980), (3) improved soil characteristics under ZT could facilitate seed predators and decay agents (Gallandt et al. 1999), and (4) mortality of potential seed predators might be reduced where continuous flooding and tillage are not used. Preliminary studies conducted in India by Kumar et al. (unpublished) showed higher postdispersal seed predation of barnayardgrass (71 vs. 29%) and caesulia (39 vs. 13%) under ZT with residue than under CT during a 1-wk period between wheat harvest and rice planting. Chauhan et al. (2010) have also reported a high rate (78 to 91%) of seed predation of grass weed species, including junglerice, goose grass [*Eleucine indica* (L.) Gaertn.], and crabgrass (*Digitaria* spp.), from the soil surface in rice fields in the Philippines. Higher seed predation under ZT than under CT has also been observed in other cropping systems (Brust and House 1988). These results suggest that ZT with surface residue will help in depleting the seedbank through higher seed predation over the time.

Similarly, ZT with residue could play an important role in enhancing weed seed decay. Under ZT, the surface soil layer has a higher proportion of weed seeds (Chauhan and Johnson 2009c; Yenish et al. 1992), higher soil moisture (Papendick and Parr 1997), and higher microbial diversity (Doran 1980; Lupwayi et al. 1998), all of which favor microbial seed decay (Gallandt et al. 2004). In a study conducted in the United States, Gallandt et al. (2004) did not observe any difference in decay of wild oat seeds under CT and ZT in a 10-mo duration. However, several studies in non–rice-based systems have reported on the role of microbes in seed decay (Chee-Sanford et al. 2006; Froud-Williams et al. 1983; Kennedy 1999; Pitty et al. 1987). Reports of higher survival of many weed seeds in the soil with fungicide seed treatments (Kumar et al. 2011; Leishman et al. 2000) provide compelling evidence that soil microorganisms contribute to seed decay. Therefore, crop management practices such as ZT and residue retention, which could enhance weed seed decay agents (microbes/fungal pathogen), might contribute to reductions in the weed seedbank in the long run.

Zero-Tillage Wheat. *Use of Weed-free Certified Seed.* Sowing crop seeds contaminated with weed seeds has been a major source for their spread. In contrast to rice, the majority of wheat farmers use their own saved seeds for sowing. Recent surveys have revealed that the majority of farmers are seeding wheat seeds containing weed seeds, particularly the littleseed canarygrass (Chhokar, unpublished data; Yadav and Malik 2005). Thirty to 67% of seed samples collected just before wheat sowing from seed drill boxes in five districts of Haryana, India, were found contaminated with littleseed canarygrass seeds, with contamination levels up to 72,500 seeds and a mean value of 5,040 seeds in a 1-ha equivalent wheat seed rate (125 kg ha^{-1}; Yadav and Malik 2005). They also collected 114 grain samples from 1999 to 2000, largely from grain markets in the same districts of Haryana, and found alarming levels of contamination with littleseed canarygrass seeds, ranging from 17,784 to 1,700,000 (mean, 266,171) seeds per 125 kg of wheat grain (Yadav et al. 2002; Yadav and Malik 2005). This suggests that the use of either certified seeds or proper cleaning of owner-saved seeds for planting is important in reducing littleseed canarygrass populations. Littleseed canarygrass seeds can easily be separated from wheat seeds using sieves because of differences in their seed size.

Zero-Tillage, Residue Management, and Planting Date. Zero-tillage, even without residues, has been found helpful in reducing the population of littleseed canarygrass (Chhokar et al. 2007; Franke et al. 2007; Gupta and Seth 2007; Malik et al. 2002). Franke et al. (2007) observed that emergence rate of all three flushes of littleseed canarygrass in wheat sown on the same date were lower in ZT compared with CT. The first emergence flush—which was the most important flush affecting crop–weed competition—was about 50% lower in ZT than in CT (Franke at al. 2007). Chhokar et al. (2007) estimated 39% lower biomass of littleseed canarygrass (based on 15 field observations) under ZT compared with CT because of lower density.

ZT, when combined with residue retention on the surface and early sowing, results in further suppression of littleseed canarygrass and other weeds of wheat. In an on-going study started in 2011 to 2012 at Karnal, India, to examine effects of date of sowing and residue mulch under ZT, we observed that at 45 DAS, littleseed canarygrass population in early planting (25 October) was 68% and 80% lower than normal (November 10) and late planting (November 25), respectively (Kumar et al., unpublished data). Similarly, residue mulch from the previous rice crop of 6 and 8 t ha^{-1} reduced emergence of littleseed canarygrass by 45 and 75%, respectively (Kumar et al., unpublished data). When early seeding and rice mulch were combined, littleseed canarygrass emergence was 83 to 98% lower compared with normal or delayed seeding without residue.

Rice residue mulch reduced weed emergence of seeded weeds in the range of 45 to 99% depending on species and mulch amount (Table 5; Kumar et al., unpublished data). At 45 DAS, emergence of littleseed canarygrass, lambsquarter, and Indian sorrel was suppressed by 45, 83, and 88%, respectively, in a 6 t ha^{-1} residue plot compared with no residue control; suppression of emergence increased to 57 to 67%, 92 to 99%, and 95 to 99%, respectively, with increase in residue mulch from 6 t ha^{-1} to 8 to 10 t ha^{-1} (Table 5; Kumar et al., unpublished data). Yellow sweet clover emergence was not significantly affected up to 6 t ha^{-1}, but residue mulch of 8 or 10 t ha^{-1} reduced its emergence by $> 95\%$. Residue mulch of 4 t ha^{-1} delayed the emergence of littleseed canarygrass but did not affect total emergence (up to 30 DAS, emergence was lower than no residue control, but by 45 DAS, it was similar; data not shown). However, emergence of lambsquarter and Indian sorrel was highly suppressed (78%), even by 4 t ha^{-1} rice residue mulch (Kumar et al., unpublished data; Table 5). Chhokar et al. (2009) observed that 2.5 t ha^{-1} rice residue mulch was not effective in suppressing weeds, but 5.0 and 7.5 t ha^{-1} residue mulch reduced weed biomass by 26 to 46%, 17 to 55%, 22 to 43%, and 26 to 40% of littleseed canarygrass, Indian sorrel, bur clover and foxtail grass, respectively, compared with ZT without residue.

The majority of farmers in RW systems, especially in northwestern IGP, burn residues of previous rice crop for its rapid disposal before wheat sowing because it can interfere with drilling. Such burning of rice straw increases the germination of littleseed canarygrass and reduces the efficacy of soil-active herbicides like isoproturon and pendimethalin (Chhokar et al. 2009).

Recent advances in planting technology have made it possible to sow wheat successfully into heavy residues and facilitated the use of residues as mulches for weed suppression. In particular, the rotary disc drill and turbo happy seeder can seed wheat in heavy residue mulch of up to 8 to 10 t ha^{-1} without any adverse effect on crop establishment (Kumar and Ladha 2011; Sharma et al. 2008).

In addition to the suppressive effects on emergence of weeds, residues can contribute to weed seedbank depletion through seed predation. Preliminary studies conducted in India indicate that postdispersal seed predation of littleseed canarygrass during a 1-wk period between wheat harvest and rice planting was 50 to 60% under ZT with residue compared with 10% under CT (Kumar et al., unpublished data). This could be one of the many reasons for lower population of littleseed canarygrass under ZT.

Planting Methods and Seed Rate. Planting methods and seed rates can also influence crop–weed competition under ZT wheat. Narrow-row planting with increased crop density can shift the competitive balance in favor of the crop. Johri et al. (1992) observed that nitrogen-phosphorous-potassium uptake by grass weeds (wild oat, bermudagrass, and littleseed canarygrass) was lower when wheat was sown with closer row spacing (15 cm), higher seed rate (150 kg ha^{-1}) and cross (bidirectional) sowing compared with wider row spacing, normal seed rate, and unidirectional sowing. Narrow row spacing (15 cm) reduced littleseed canarygrass biomass by 16.5% compared with normal spacing of 22.5 cm (Mahajan and Brar 2002). Higher seed rate of 150 kg ha^{-1} was found helpful in reducing populations of littleseed canarygrass, Indian sorrel, and yellow sweet clover compared with a normal seed rate of 125 kg ha^{-1} (Anonymous 2001). Kurchonia et al. (1993) reported lower total weed biomass, including littleseed canarygrass, when wheat was sown with bidirectional (cross) method (20 by 20 cm) compared with unidirectional sowing with 20-cm row spacing. Similarly, multilocation trials conducted across wheat-growing zones under the All India Co-ordinated Wheat and Barley Improvement Project have shown advantages of cross-sowing (22.5 cm by 22.5 cm) compared with unidirectional sowing at a row spacing of 22.5 cm with regard to weed suppression and wheat productivity gain (Mongia et al. 2005).

Competitive Cultivars. Crop cultivars vary in their growing habit, which can substantially affect the crop–weed competitive balance. Wheat varieties with faster early growth, earlier canopy formation, spreading habits and greater height are less susceptible to weed competition (Balyan and Malik 1989; Paul and Gill 1979). Although, the competitive ability of wheat is often negatively associated with yield potential under weed-free environments, the magnitude of yield loss under weedy conditions is greater in high-yielding, less competitive dwarf wheat cultivars than in tall competitive cultivars (Challaiah et al. 1986). Seed size also influences weed competition through its effect on early vigor (Spitters and Van Den Berg 1982).

Even among high-yielding cultivars, there is a large difference in weed competitiveness. Balyan et al. (1991) and Singh et al. (1990) found that wheat cultivars 'WH-147' and 'HD-2285' with medium height were more competitive with wild oats and other weeds compared with other cultivars, such as 'HD-2009', 'WH-291', and 'S-308'. Under weedy conditions, 27 to 28% yield was reduced in cultivars HD-2285 and WH-147, whereas in HD-2009, yield losses due to weeds were 59% (Singh et al. 1990). Similarly, Kumar (2003) evaluated competitive ability of wheat cultivars against weeds, including littleseed canarygrass, and found 'HD-2687', 'PBW-343', and 'WH-542' most weed competitive. Under timely planting conditions, PBW-343 and WH-542 were equally competitive with littleseed canarygrass (Chahal et al. 2003; Kaur et al. 2003; Mahajan and Brar 2002), but under delayed sowing conditions, PBW-343 is superior to other cultivars against littleseed canarygrass (Kaur et al. 2003). Rapid growth and more tillering are the important traits leading to early canopy cover in these varieties and weed competitiveness.

Crop Rotation. Rotating crops that have dissimilar life cycles or cultivation practices is a very effective cultural practice for disrupting life cycles and improving control of problematic weeds like littleseed canarygrass (Chhokar et al. 2008). In heavy soils, infestations of wild oats that predominated in maize–wheat systems were completely eliminated by growing rice instead of maize (Gill and Brar 1975). Similarly, the incidence of littleseed canarygrass was greatly reduced in RW systems by growing clovers or oats for fodder 1 in 3 yr in place of wheat after rice (Chhokar et al. 2002; Gressel 1993). Intensification of the RW system by including short-duration vegetables (pea or potato) followed by late wheat can also improve weed control without herbicide applications (Chhokar et al. 2008).

Water and Nutrient Management. Water and nutrients can be manipulated to favor crops and not weeds. High moisture in RW systems favors moisture-loving weeds like littleseed canarygrass, Indian sorrel, and foxtail grass (Singh et al. 1995). Because wheat can germinate under drier conditions than can many weeds (Chhokar et al. 1999), sowing under dry conditions can facilitate reduced weed emergence and competition. Similarly, placement of fertilizer in the crop root zone can shift weed–crop competition in favor of the crop. Under ZT, seed drills can place basal applications of fertilizer below the seeds, thereby suppressing weeds, compared with a farmer's practice of broadcasting seeds and fertilizers.

Conclusions and Future Research Needs

Alternative nonchemical weed management strategies are needed to reduce dependence on herbicides for weed control under ZT systems. It is challenging to manage weeds under ZT without herbicides. Nonchemical weed management is more difficult in ZT rice than in ZT wheat. However, when multiple tactics for weed control are integrated, dependence on herbicides can be reduced and perhaps eliminated in some situations. In ZT rice production systems, integration of stale seedbed, residue mulching, sesbania coculture, competitive cultivars, and appropriate agronomic practices, including high-quality seed, seeding rate, crop geometry, crop establishment methods, water management, and strategies to reduce weed seedbank by minimizing seed input and enhancing seed mortality, can reduce weed infestations and hence herbicide use. In ZT wheat, an integrated approach combining rice residue retention, earlier sowing (last week of October) of certified/clean seeds, higher seed rates and narrow row spacing of competitive cultivars, crop rotation, and fertilizer and water management can drastically reduce weed problems in ZT wheat. However, additional research on the following aspects will help in further developing and strengthening nonchemical weed management strategies of ZT RW systems:

- Determining emergence periodicity of key weed species of rice and wheat under ZT. This information will help in making weed control timing decisions and maximizing effectiveness of both chemical and nonchemical weed control approaches.
- Quantifying effects of different crop residue mulches (rice, wheat, sesbania, mungbean, etc.) on different weed species and how much residue of these crops is required to achieve optimum suppression of different weed species without affecting crop establishment.
- Identifying vulnerabilities in the life cycles of key weed species of ZT rice and wheat by studying weed population dynamics under ZT.
- Quantifying short- to long-term effects of inclusion of summer annual legume cover crops in the systems on weed suppression during cover cropping and after its termination in ZT rice crop.
- Developing weed-competitive cultivars with anaerobic germination traits so that early flooding can be used in ZT-DSR for weed suppression.
- Estimating season-long seed predation potential under CT and ZT and mechanisms by which seed predation may be enhanced.
- Developing weed management strategies for emerging problematic weed species such as weedy rice, Chinese sprangletop, and crowfootgrass.
- Estimating the role of irrigation water and manure/compost in seed dissemination and developing strategies to minimize it.

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