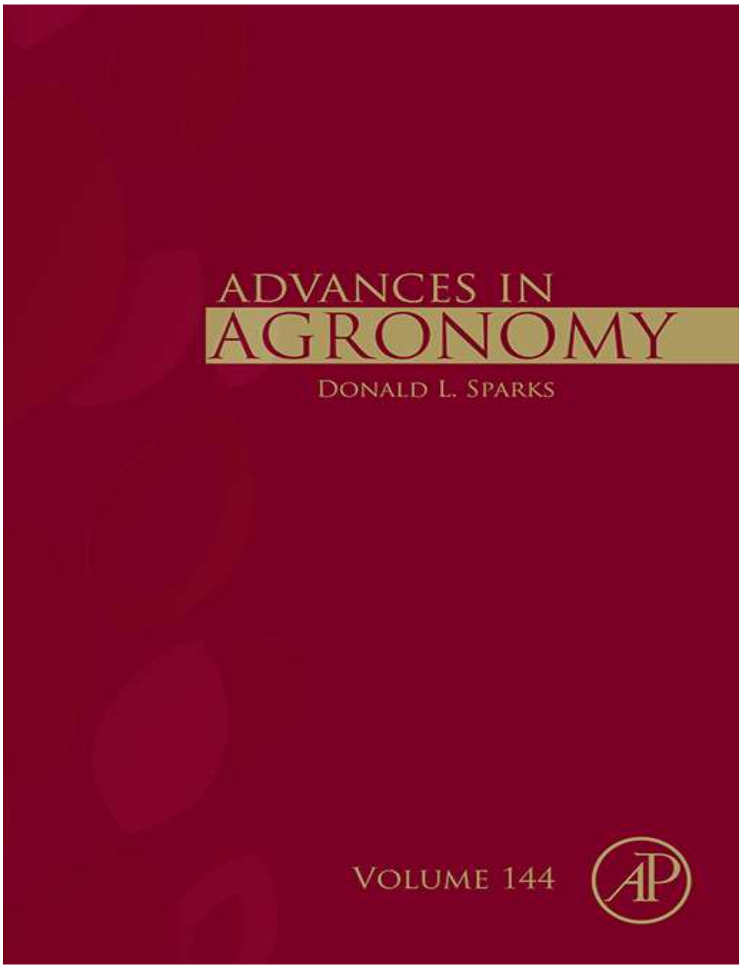

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CHAPTER TWO

Preventive Weed Management in Direct-Seeded Rice: Targeting the Weed Seedbank

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Abstract

In Asia, direct-seeded rice (DSR) is becoming popular as an alternative to puddled transplanted rice (PTR) due to its potential to save scarce resources (labor, water, and energy), reduce greenhouse gas emissions, improve soil physical properties,

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and increase yields in rotational crops. However, weed management in DSR is more difficult because the initial size differential between weeds and rice is small, reducing crop competitiveness and limiting opportunities for selective control measures including flooding. In this context, preventive approaches—those which focus primarily on limiting dispersal and persistence of weed propagules—may play a critical role in complementing the current reliance on curative tactics such as herbicides. Greater understanding and integration of preventive approaches in DSR may reduce the risks of herbicide resistance development, limit adverse effects of herbicides on human health and the environment, and lower the overall weed management costs. However, information on preventive weed management in DSR is relatively limited. Therefore, the central objectives of this review are to: (i) summarize existing knowledge regarding preventive strategies; (ii) discuss key integrated preventive weed management approaches that have the greatest potential for practical application in DSR systems; and (iii) identify knowledge gaps that limit our ability to optimize preventive approaches. Based on an extensive review of existing literature, we conclude that (i) *Minimizing weed seed production* in the field is critically important for managing weed seedbanks in DSR, but that given seed dispersal in both time and space, prevention of seed production from neighboring bunds, rice–fallow land and irrigation channels bordering DSR areas may be equally important; (ii) *Minimizing dispersal* of weed seeds into DSR fields may be a practical approach for species that are dispersed primarily by humans (e.g., as contaminants in crop seeds or through irrigation canals), but not for species that are dispersed primarily by other means (wind and birds); (iii) *Promotion of seed predation* may be a useful strategy in managing certain weed species in DSR—especially where zero-tillage is used—but more research is needed on the identity of seed predators and management factors that promote their activity; (iv) available evidence suggests that the potential for *promotion of seed decay* is limited in scope but may be valuable for the management of certain relatively nonpersistent weeds in some cropping systems; (v) strategies that *stimulate fatal germination* of weed seeds (e.g., stale seedbed) appear to be one of the most promising means of prevention in DSR, but increased information on the mechanisms and timing of dormancy release for key species is needed to optimize and enhance the value of this approach; (vi) *Prevention of weed germination and emergence* in DSR through mulching—especially in zero-till systems—has proven benefits, but its widespread applicability is limited by the economic tradeoffs associated with using mulch as a source of livestock feed; and (vii) development of anaerobic germination (AG)-tolerant rice cultivars and complementary flooding strategies which can tolerate anaerobic conditions/flooding hold great potential for the suppression of weeds in DSR. Successful integration of preventive approaches for managing weeds in DSR will depend on the development of multidisciplinary approaches which are biologically effective, economically feasible, and socially acceptable. Preventive weed control measures alone are unlikely to be sufficient for the effective and economical management of weeds in DSR systems, but their integration with curative approaches should reduce weed management costs and increase both the likelihood of adoption of DSR and the realization of its benefits for food security.

1. INTRODUCTION

Rice is the dominant staple food of about 4 billion people worldwide, providing about 33% of the total caloric intake of most Asians (Dawe et al., 2010). The global rice demand will continue to increase from 479 million tons (milled rice) in 2014–15 to 544 million tons in 2029–30 (IRRI, 2016). Given the projected population growth, it is estimated that the annual rice yield growth in the next 10 years will have to increase to around 1.2%–1.5% from its current rate of less than 1% (FAO, 2014; Mohanty et al., 2010, 2013). The actual yield growth in the past decade has been below this target mainly because of the combined effects of the lack of progress in (1) raising the yield potential of rice and (2) reducing yield losses caused by abiotic and biotic stresses and natural disasters (IRRI, 2008). More specifically, productivity has been stagnated or declined by environmental degradation (Pingali et al., 1997), biological constraints including weeds (Rao et al., 2007), the increasing scarcity of appropriate land, labor, and water resources (Rosegrant et al., 2002), and the increasing variability in climate (FAO, 2014).

To address many of these constraints, direct-seeded rice (DSR) production systems are being developed and promoted to substitute inefficient labor- and energy-intensive soil puddling and transplanting (PTR) which is currently practiced widely (Kumar and Ladha, 2011; Rao and Ladha, 2011; Rao and Nagamani, 2007, 2010; Rao et al., 2007). Depending on economic and agroecological conditions, rice production systems vary in the method of establishment (transplanted or direct-seeded) and the level and type of tillage (none, dry, or wet). In DSR, seeding may be done in dry soil (dry-DSR), in puddled or wet soil (wet-DSR), or in standing water (water seeding) (Kumar and Ladha, 2011; Rao et al., 2007). In dry-DSR, dry seeds are sown into the soil which is not puddled but which may be either dry tilled [conventional tillage (CT)–dry-DSR)] or zero-tilled (ZT–dry-DSR). In wet-DSR, pregerminated sprouted seeds are sown into soil that has been puddled (wet-tilled) as in PTR. The method of crop establishment in DSR can either be broadcasting (manually or mechanically using aeroplane or power sprayer) or line sowing (using either a drill or drum seeder or manually by dibbled method).

In areas where labor scarcity persists but water costs are low, farmers may be encouraged to shift to wet-DSR or mechanical transplanting without necessarily changing tillage practices. Farmers have incentives to shift to dry-DSR either with dry tillage or with zero or reduced tillage in areas where both labor and water are emerging as major constraints (Kumar and Ladha, 2011; Pandey and Velasco, 2005; Rao et al., 2007). Dry-DSR can help conserve water by avoiding extended periods of flooding and the water-intensive practice of puddling. In addition to savings on water, labor, and energy, dry-DSR may provide several other potential benefits compared to PTR which include: (1) higher net economic returns (due to lower costs); (2) reductions in methane emissions; and (3) improvements in soil physical condition and yields of nonrice crops planted in rotation like wheat (Gathala et al., 2013; Humphreys et al., 2004; Kumar and Ladha, 2011; Ladha et al., 2016; Padre et al., 2016).

Despite the multiple potential benefits associated with DSR production systems, however, their adoption has been seriously constrained by weed management tradeoffs. In DSR, weed management is considered a serious challenge and the risks of yield losses due to weed competition are relatively higher than in PTR because (1) the potential of using early flooding to suppress initial flushes of weeds early in the season is limited and (2) rice seedlings in DSR are less competitive with concurrent emerging weeds compared to transplanted rice because of the absence of a size differential between the rice and weeds in DSR (Johnson and Mortimer, 2005; Kumar and Ladha, 2011; Rao et al., 2007; Singh et al., 2011).

In most DSR systems, farmers are turning to herbicides to improve the timeliness of weed control and to overcome labor constraints (Rao and Ladha, 2013; Rao and Nagamani, 2013; Rao et al., 2007). Although herbicides play an important role in reducing weed competition and in helping to ensure adequate yields under DSR, overreliance on herbicides poses both economic and environmental risks. It can result in the evolution of herbicide-resistant weed populations (Gressel and Baltazar, 1997; Kumar and Ladha, 2011) and in shifts in weed communities (Ho, 1991; Rao et al., 2007) that reduce herbicide efficacy and increase costs, as newer and more expensive herbicides may be required. Herbicides can also contaminate water sources (Karpouzas et al., 2006; Seiber, 1987) and are thought to contribute to human health problems (Pingali and Marquez, 1996), resulting in a legislation to limit their use in some cases (Jayasumana et al., 2014).

In response to these weed management challenges in DSR, as well as the potential problems associated with the overuse of herbicides, several recent reviews have outlined integrated approaches to manage weeds such as the use of competitive cultivars, changes in seed rate, timing and geometry, use of residue mulching, crop rotation, water management, nutrient management, and mechanical management (Kumar et al., 2013; Matloob et al., 2015; Rao et al., 2007). These reviews have also highlighted the potential importance of preventive measures including the promotion of seed predation, decay, and fatal germination as important components of integrated weed management in DSR. However, detailed reviews on the potential of preventive approaches based on knowledge of the ecology of key weed species of DSR are currently unavailable.

For the purposes of this review, we define "preventive" weed management practices as those which occur either prior to planting of the crop (e.g., during fallow periods or in rotational crops) or outside of the crop production area (e.g., in adjacent bunds, irrigation canals, or seed-distribution channels). These approaches include efforts to limit the dispersal and persistence of weed propagules (seeds and vegetative propagules) in both time and space and creating conditions which prevent weed emergence within the crop (Fig. 1). Such approaches contrast with "curative" approaches which target existing weeds within the crop and include a diverse set of tactics that can be either direct (e.g., herbicide application, hand weeding, mechanical weeding, and flooding) or indirect (e.g., use of competitive cultivars, and manipulating seed rate, crop geometry, and fertilizer management). Since weeds are unlikely to be eliminated from agricultural fields, preventative and curative approaches are important and complementary. However, far more attention has been given to curative approaches. Therefore, a close examination of preventative approaches may provide opportunities for improved weed management. Preventative approaches may take on greater importance in DSR since traditional curative approaches associated with PTR (i.e., transplant size differential; and early flooding) are not applicable to DSR.

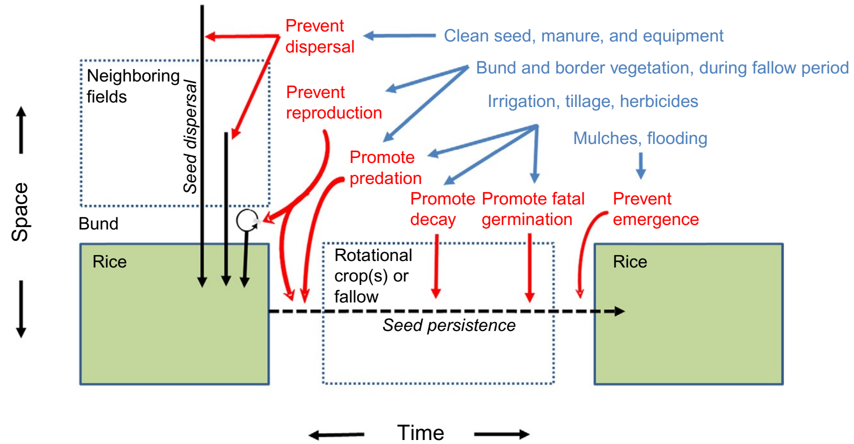

Fig. 1 Conceptual framework of preventive weed management in direct-seeded rice.

Therefore, the central goal of this review is to identify opportunities for greater integration of preventive approaches for managing weeds in DSR in order to lower both the economic and environmental costs associated with its adoption. The specific objectives are:

- To summarize existing knowledge regarding preventive strategies and tactics, including those that seek to limit the dispersal and persistence of weed propagules (Fig. 1).
- Based on current knowledge, to discuss key integrated preventive weed management approaches that appear to have the greatest potential for practical application in a range of DSR systems.
- To identify knowledge gaps that limit the ability to optimize preventive approaches and suggest research priorities for improving preventive weed management in DSR systems so that the many potential benefits of DSR can be realized.

2. PREVENTIVE WEED MANAGEMENT STRATEGIES

2.1 Preventing Reproduction

The most critical element of successful long-term weed seedbank management is the prevention of weed reproduction. Weed seedbank densities can be greatly reduced by eliminating seed production for a few years (Buhler et al., 1997) or can increase rapidly if weeds are allowed to produce seed. Because prevention is often far less expensive than treatment, "zero seed rain" strategies are sometimes advocated (Gallandt, 2006; Norris, 1999). Although *zero* seed rain may not be a realistic nor optimal approach in all situations, *minimizing* seed rain is an important goal—especially in DSR—and the extra initial costs associated with reducing weed seed rain may be offset by lower weed management costs in future years.

The production of propagules of key weeds in DSR often occurs "internally," within the rice field itself, and is typically addressed through curative management practices discussed in detail in other reviews (Kumar and Ladha, 2011; Kumar et al., 2013; Matloob et al., 2015; Rao et al., 2007). However, the substantial production of propagules of important weeds of DSR can also occur "externally" during fallow periods or in rotational crops that follow rice harvest, or in field borders, bunds, or fallow fields adjacent to rice production areas. Depending on the weed species and the cropping system, such external seed production—coupled with dispersal in either time or space—may represent a major input to the DSR weed seedbank.

Rice agroecosystems contain two broad habitat types external to the field which may contribute significantly to the weed seedbank: the bund (levee) and the ditch (irrigation canal) (Bambaradeniya and Gunatilleke, 2002; Chandrasena, 1988). Ditch habitats usually remain flooded throughout much of the year and contain many submerged, floating-leaved, and free-floating aquatic weeds, whereas weed communities of bunds are mainly terrestrial (Chandrasena, 1988).

The abundant growth and seed production of annual weeds on paddy field bunds and their addition to the soil during land preparation are reportedly common in rice agroecosystems in Asia (Rao and Moody, 1986). For example, a survey of weed species on bunds in lowland rice fields in Sri Lanka found an abundance of semiaquatic and terrestrial weed species including *Isachne globosa* (Thunb.) O. Ktze., *Eragrostis unioloides* (Retz.) Nees ex Steud., *Panicum repens* L., *Fimbristylis miliacea* (L.) Vahl, *Cyperus pilosus* Vahl, *Commelina diffusa* Burm. f., *Paspalum commersonii* Lam., and *Cyperus iria* L. (Chandrasena, 1988). In the absence of competition from a crop and intervention, these species have potential to produce enormous numbers of seeds (Table 1).

Indirect evidence from several studies suggests that seed production by many weed species in irrigation channels may also contribute to weed problems in adjacent DSR fields. In a lowland rice field in China, Zuo and Qiang (2008) found floating seeds of 26 weedy species belonging to 17 families and suggested that these species could readily disperse via irrigation into rice fields. Similarly, Li and Qiang (2009) found seeds of 74 weedy species in irrigation water, with roughly half belonging to the Poaceae, Asteraceae, and Polygonaceae families. Although the origin of these seeds is unknown, their reproduction along irrigation canals can clearly contribute to weed problems in irrigated DSR systems.

Production of weed seeds during the fallow period after rice harvest can also be substantial. For example, in Bihar, India, seeds of *Caesulia axillaris* Roxb. and other weed species that are immature at the time of rice harvest can grow rapidly after the removal of the rice canopy and then produce mature seeds (V. Kumar, personal observation). Similarly, in Odisha, India and South Sumatra in Indonesia, where rice–fallow is the dominant cropping system, weeds grow and produce seeds and add to the seedbank during the fallow phase (V. Kumar, personal observation). Similarly, in the rice–rice cropping systems of Southern Bangladesh, during the short fallow period between harvests of boro (dry) season and planting of succeeding T. Aman (wet) season rice, weeds such as *Echinochloa colona* (L.) Link. can grow and produce a large number of seeds and, hence, can contribute to

Table 1 Maximum Reported Seed Production by Major Grass, Broadleaf, and Sedge Weed Species of Rice

Weed Species	Maximum Seeds/Plant (#)	References
Grasses		
Cynodon dactylon	2000	Eliáš (1986)
Dactyloctenium aegyptium	66,000	Holm et al. (1997)
Digitaria longiflora	60,000	Galinato et al. (1999)
Echinochloa colona	100,000	Ampong-Nyarko and De Datta (1991)
Echinochloa crus-galli	80,000	Norris (1996)
Echinochloa glabrescens	11,300	Kim and Moody (1989a,b)
Eleusine indica	135,000	Holm et al. (1997)
Eragrostis tenella	140,000	Galinato et al. (1999)
Ischaemum rugosum	40,000	Galinato et al. (1999)
Leptochloa chinensis	90,000	Dhawan (2007)
Rottboellia cochinchinensis	16,000	Mercado (1978)
Broadleaved		
Aeschynomene aspera	5340	Datta and Banerjee (1976)
Aeschynomene indica	9115	Datta and Banerjee (1976)
Ageratum conyzoides	94,772	Rodríguez and Cepero (1984)
Alternanthera sessilis	4356	Datta and Banerjee (1976)
Amaranthus spinosus	235,000	Holm et al. (1997)
Ammannia baccifera	5855	Datta and Banerjee (1976)
Celosia argentea	57,000	Galinato et al. (1999)
Commelina benghalensis	2300	Yoshida et al. (2006)
Commelina diffusa	1000	Galinato et al. (1999)
Cyanotis axillaris	2000	Datta and Banerjee (1976)
Eclipta prostrata	17,000	Holm et al. (1997)
Euphorbia hirta	12,816	Datta and Banerjee (1976)
Euphorbia thymifolia	6075	Datta and Banerjee (1976)

Table 1 Maximum Reported Seed Production by Major Grass, Broadleaf, and Sedge Weed Species of Rice—cont'd

Weed Species	Maximum Seeds/Plant (#)	References
Lindernia crustacea	6130	Datta and Banerjee (1976)
Ludwigia hyssopifolia	250,000	IRRI-RKB (2016)
Monochoria vaginalis	119,000	Kim and Moody (1989a,b)
Murdannia nudiflora	2200	Galinato et al. (1999)
Portulaca oleracea	259,000	Waterhouse (1994)
Sphenoclea zeylanica	25,000	Datta and Banerjee (1976)
Synedrella nodiflora	6000	Galinato et al. (1999)
Trianthema portulacastrum	52,000	Ampong-Nyarko and De Datta (1991)
Sedges		
Cyperus difformis	278,500	Kim and Moody (1989a,b)
Cyperus iria	5000	Galinato et al. (1999)
Fimbristylis miliacea	146,700	Kim and Moody (1989a,b)
Fimbristylis dichotoma	6500	Galinato et al. (1999)

the seedbank (V. Kumar, personal observation). If environmental conditions are favorable, *Striga hermonthica* (Delile) Benth in West Africa (Rodenburg et al., 2006) and several other weeds continue to reproduce after crop harvest, contributing considerably to the total seed production. Abundant seed production of annual weeds such as *F. miliacea* and *Echinochloa glabrescens* Munro ex Hook. F. in the field during the fallow period was observed (Rao and Moody, 1986). Such seeds may persist through rotational crops and reduce yields or increase weed management costs in DSR in subsequent years.

2.1.1 Preventing Reproduction on Bunds and Borders

Preventing the production of weed seeds in fields and irrigation channels bordering DSR production areas may be logistically challenging and prohibitively expensive in many circumstances, since ownership (and management decisions) of those areas is often distinct from ownership of the DSR field itself. Raising the awareness of farmers and using the community action approach are needed to prevent the production of weed seeds in such places. The prevention of weed seed production on bunds within and adjacent to DSR fields is practically feasible but limited data are available on its role in suppressing weeds in DSR and on the economics associated with it, which would be helpful in inviting the attention of farmers. Such weeds may be prevented from producing seeds by controlling them through the application of herbicides or hand weeding or mowing/brush cutter, or by sowing weed-suppressive green manure or smother crops.

In some cases, rice farmers may be reluctant to remove weeds from bunds as they may see these as sources of green fodder, a means of protecting bunds from erosion, or a refuge for beneficial insects. For example, Weerakoon et al. (2011) reported that farmers in DSR systems in Sri Lanka would not spray herbicides to kill the weeds on the bunds because of their belief that herbicide use would reduce the strength of the bund. Many entomological studies suggest that bund vegetation, including weeds, may be an important habitat for beneficial including spiders and may contribute significantly to the biological control of important insect pests (Marcos et al., 2001). Similarly, bund vegetation may play an important role in preserving predators of weed seeds (see Section 2.3). Therefore, optimal bund management requires an assessment of tradeoffs associated with different strategies.

One approach to prevent seed production on bunds or in subsequent rotational crops is the use of cash crops, fodder crops, or smother crops to suppress weeds. For example, green manure plants like *Gliricidia* can be grown on the bunds (Patra and Bhattacharyya, 2008) so that weeds will not have space to grow and set seed. Fodder crops like Napier grass may also serve this purpose (Joshi, 2015), while providing higher quality feed for livestock than may be available through foraging (Leenanuruksa et al., 2014). The forage grass variety Nandi of *Setaria sphacelata* Stapf. Eex Hubb. was found to be suitable for planting on bunds of fields up to an altitude of 2000 m (CVRC Notification no. 2(E) dated January 03, 1983) (Pandey and Roy, 2011). Gutteridge (1983) estimated that rice bunds have the capacity to produce forage legume dry matter yields of 5–50 kg/100 m^2/year (Devendra and Sevilla, 2002). Growing grasses (ICARNEH, 2013) and the production of cash crops like vegetables on bunds (http://www.crri.nic.in/crri.sucstory.htm), if accompanied by timely weed management, may also reduce weed seed and propagule inputs while supplementing farmers' income and/or food (ICARNEH, 2013; http://www.crri.nic.in/crrisucstory.htm). Several rice farmers in China plant peanut, soybean, yardlong bean, taro, etc., on rice bunds (Nilda Burgos, personal observation). Depending on the choice of bund vegetation, ecosystem services including insect pest regulation may also be enhanced through these approaches (Gurr et al., 2011; IRRI, 2010; Way and Heong, 1994).

2.1.2 Prevention of Reproduction During Fallows

Prevention of seed production during the fallow period is also potentially a low-cost and valuable approach in preventing the build-up of the seedbank or perennial vegetative structures under DSR. This can be done during the long fallow period after rice harvest in the rice–fallow system in a single cropping system or during the short fallow period between harvest of rotational crop and planting of succeeding rice crop in doubling cropping systems.

In situations where immature weeds or perennating structures are present following harvest, tillage, or herbicide applications may prevent seed maturation or vegetative expansion (Diallo and Johnson, 1997; Haefele et al., 2000). Greater monitoring of potential seed production during this postharvest interval and the evaluation of potential methods for preventing weed seed maturation during this time would be helpful in guiding growers in their decision making. For example, cover cropping has been found effective in suppressing weeds during fallow periods in tropical, subtropical, and temperate regions (Akobundu et al., 2000; Brainard et al., 2011; Kumar et al., 2008, 2011; Teasdale et al., 2007). In addition, cover crops can be beneficial in improving soil health and the productivity of succeeding crops, especially if legumes are used. Saito et al. (2006) observed increased yields of direct-seeded upland rice and reduced weed growth in the subsequent rice growing season with the replacement of the natural fallow vegetation with stylo (*Stylosanthes hamata*), established as a relay crop with upland rice, in the short-term fallow systems. However, farmers may not be aware of the longer-term impact of this approach on weed populations or may not be willing or able to pay for the additional costs of weed management during this period. A clean fallow period has been identified as an important strategy for drawing down weed seedbanks in temperate cropping systems (Mohler, 2009; Nordell and Nordell, 2007) but the economic and biological implications of this strategy in DSR have not been extensively explored.

2.2 Limiting Dispersal

Propagule dispersal is important for weed population and community dynamics and for the spread of weeds in agroecosystems. Dispersal allows weeds to colonize new areas and is often a critical element in determining the rate of spread of weedy and invasive species (Baker, 1991; Howe and Smallwood, 1982). In addition, dispersal serves to avert or minimize intraspecific competition among succeeding generations of weeds and ensures spatial heterogeneity (Cantrell and Cosner, 1991) in the rice paddy.

An understanding of the seed dispersal mechanisms of weeds in DSR systems can help in identifying ecological weed management strategies based on dispersal prevention. Such a strategy depends on knowledge of dispersal mechanisms of particular key species (Table 2) and identification of practical and economical methods for prevention. For species with propagules that are primarily dispersed through human activities like contaminated crop seed, practical prevention may be relatively straightforward and feasible by switching to certified seeds that are free from weed seeds. However, for those with independent dispersal mechanisms such as long-distance wind dispersal, this approach would not be feasible.

2.2.1 Dispersal via Rice Seed Contamination

The movement of weed seeds via crop contamination is an important mechanism of dispersal for certain weed species especially in DSR systems in Asia, since high seeding rates are used and the seeds are sown directly into the main field. Weeds which mature at the same time as rice are often harvested and threshed with the rice, resulting in contamination (Rao and Moody, 1990). Rice seeds contaminated with weed seeds may introduce new species to rice fields or add to an existing weed population. For example, *Leptochloa chinensis* (L.) Nees was observed for the first time in rice paddies of northern Italy very recently and was presumed to have been introduced via contaminated rice seeds (Benvenuti et al., 2004). *E. colona* also often matures simultaneously with rice and becomes a contaminant for subsequent seedings (Dubey, 2004; Rao and Moody, 1990). Seed contamination is also considered an important mechanism by which herbicide resistance can be transferred from farm to farm (Pratley et al., 1995). Studies on incoming and outgoing germplasm lines by the International Rice Research Institute (IRRI) seed health unit have identified seeds of 20 weed species as contaminants of rice seed lots, with *Echinochloa* spp. being the most frequent with a maximum of 436 seeds per kg of rice (Huelma et al., 1996). Thus, in preventing weed seed contamination and dissemination through exchanged germplasm, thorough processing must be done prior to shipment.

Dispersal via seed contamination is a special consideration in regions where farmers save their own seeds rather than use certified seeds. For example, in Vietnam, the majority of farmers (81%) keep seeds for successive

Table 2 Dispersal Mechanisms Reported With Key Weed Species of Rice[a]

Name of the Weed	Dispersed by[b] CSAN Crop	WAHY Water	WIAN Wind	MAANEN Manure	FMAN Machinery	ANMY Ants	BIEN Birds	CAEPEN Cattle	HUAN Human	References
Grasses										
Echinochloa colona	■	■	■					■		Rao and Moody (1990), Sen (1981), Kaul (1986), and Majumder (1962)
Leptochloa chinensis	■									Holm et al. (1997)
Dactyloctenium aegyptium	■	■					■	■		Tanji and Taleb (1997)
Eleusine indica				■				■		Rodríguez et al. (1983)
Ischaemum rugosum	■				■					Fujisaka et al. (1993) and Antigua (1993)
Rottboellia cochinchinensis	■	■		■	■			■		Holm et al. (1997) and Thomas and Allison (1974)
Oryza longistaminata	■									Parker and Dean (1976)
Digitaria ciliaris	■			■	■				■	Takabayashi et al. (1979)
Cynodon dactylon	■	■		■	■			■		Holm et al. (1997)
Paspalum distichum		■								Ikeda et al. (1983)

Continued

Table 2 Dispersal Mechanisms Reported With Key Weed Species of Rice—cont'd

Name of the Weed	Dispersed by									References
	CSAN	WAHY	WIAN	MAANEN	FMAN	ANMY	BIEN	CAEPEN	HUAN	
	Crop	Water	Wind	Manure	Machinery	Ants	Birds	Cattle	Human	References
Broadleaves										
Eclipta prostrata	■	■								Rao and Moody (1990), Jauzein (1991), and Quisumbing (1923)
Portulaca oleracea						■				Li and Melati (1999)
Trianthema portulacastrum				■						Tadulingam and Venkatanarayana (1985)
Alternanthera sessilis		■	■			■				Soerjani et al. (1987a,b), Pancho (1986), and Datta and Biswas (1979)
Amaranthus spinosus		■	■							Holm et al. (1997)
Amaranthus viridis				■				■	■	Rodríguez et al. (1983)
Murdannia nudiflora		■	■	■				■	■	Harper (1977)
Ageratum conyzoides		■							■	Johnson (1971) and Stadler et al. (1998)

Commelina benghalensis				■	■			■		Riar et al. (2010)
Lindernia antipoda	■									Rao and Moody (1990)
Phyllanthus urinaria		■			■		■	■	■	Soerjani et al. (1987a,b)
Marsilea minuta		■					■		■	Rodgers (1993)
Eichornia crassipes		■	■				■	■	■	Batcher (2000)
Sedges										
Cyperus difformis	■									Rao and Moody (1990)
Cyperus iria	■									Rao and Moody (1990)
Cyperus rotundus		■			■					A.N. Rao (unpublished data)
Fimbristylis dichotoma	■	■		■	■					Tasrif (1989)

[a]Reported mechanisms are *shaded*.
[b]CSAN = crop seed (Anthropochory); WAHY = water (Hydrochory); WIAN = wind (Anemochory); MAANEN = manure (Anthropochory and Endozoochory); FMAN = farm machinery (Anthropochory); ANMYAnts (Myrmechory); CAEPEN = cattle and other animals (Epizoochory and Endozoochory); BIEN = birds (Endozoochory); HUAN = human activities Including tourism (Anthropochory).

crops, with less than one in five farmers exchanging seeds with neighbors or buying certified seeds (Luat et al., 1998). The quality of this saved seed is often poor, with many weed seed contaminants. For example, Mai et al. (1998) in Vietnam reported 466 weed seeds per kg of rice seed, 47-fold higher than the purity level permitted nationally. In Bangladesh, *Echinochloa crus-galli*, *E. colona*, *Cyperus difformis* L., and *Scirpus* spp. seeds were found in farmer-saved rice seeds (Islam et al., 2003). In another study in Nueva Ecija, Philippines in 1991, about 97% of seed samples collected from farmers' stock of processed and stored seeds were found contaminated with seeds of *Echinochloa* spp., *Ischaemum rugosum*, and *F. miliacea* (Fujisaka et al., 1993). They observed about 87 seeds of *Echinochloa* in 1 kg rice seed.

Dispersal through seed contamination is particularly important for species like weedy rice/red rice (*Oryza sativa* L.) and is a primary mechanism for weeds to invade rice fields. In many countries where DSR is practiced, weedy rice has emerged as a major threat (Baki et al., 2000; Kumar and Ladha, 2011; Rao and Chauhan, 2015; Ziska et al., 2015). It has been estimated that even just two red rice seeds per kg of rice, seeded in a rice field, can produce 100 kg/ha of red rice within three seasons (Noldin, 2000). In many Asian countries, seed contamination far exceeds this level, particularly among farmers who save their own seeds. In Vietnam, 314 weedy rice seeds were found per kg of rice seed (Mai et al., 1998). Another survey in Vietnam found that more than one-third of rice seed samples were contaminated with weedy rice seeds (Mai et al., 2000). In Thailand, farmers generally save seeds or obtain these from other farmers' apparently clean crop. Maneechote et al. (2004) found up to 4000 weedy rice seeds in 1 kg of an apparently clean seed. In Arkansas, USA, seed contamination is thought to be an important factor contributing to the spread of weedy/red rice (Norsworthy et al., 2007). Although there is theoretically zero tolerance for red rice in certified seeds (Anonymous, 2006), several consultants report that seed contamination in certified seeds occurs. Moreover an uncertain number of farmers plant noncertified seeds for which contamination with red rice is not regulated.

Among the many mechanisms of dispersal, contamination of rice seeds with weed seeds may be among the most practical and important to prevent. Prevention of seed contamination is more important in DSR than in conventional transplanted systems since more seeds are typically used per acre and seeds are sown directly into the field. Therefore, screening the rice seeds for weed seed contamination and using certified seeds are particularly important in DSR and are essential components in weed management

(Chin and Mortimer, 2002; Mortimer et al., 2000; Rao and Moody, 1990; Ziska et al., 2015).

2.2.2 Dispersal via Machinery/Equipment Movement

Farm machinery can easily transport weed seeds, rhizomes, and stolons from one place to another (Klingman et al., 1975). Since adoption of DSR is associated with the movement of planting equipment between fields and farms, this is a potentially important mode of dispersal of weed seeds and propagules. Field inspections by Sahid et al. (1995) in the MUDA area of Malaysia revealed that cultivation equipment and tractor tires often carry dirt and soil contaminated with weed seeds, rhizomes, and stolons from infested rice fields. Greater prevalence of perennial weeds which requires fragmentation for dissemination and establishment in conventionally tilled farms was also observed (Zelaya et al., 1997). Recently, combine harvesting has become more popular in many Asian counties, exacerbating the spread of weed propagules via harvesters and increasing the chances of contamination of rice seeds with weed seeds. For example, in Malaysia, the widespread occurrence of weedy rice is linked with the increased use of combine harvesters (Vaughan et al., 1995). The simulations by Ballareâ et al. (1987) in another context revealed that seed dispersal by combine harvesters can strongly contribute to the success and growth of weed populations.

Hence, the sanitation of equipment is an important practice for minimizing the dispersal of weed seeds in DSR via planting and harvesting equipment. Efforts to wash equipment between different fields may help reduce weed seed dispersal as well as the training of service providers to clean equipment between fields and farms. Incentivising this practice may be challenging given the increased costs it would entail. More information and awareness on the importance of dispersal via equipment, especially in areas with weedy rice and herbicide-resistant weeds, will be needed in determining the significance and practicality of this approach.

2.2.3 Dispersal via Irrigation Water

Irrigation water often contains weed seeds that can be introduced into agroecosystems (Fiore and Schroeder, 1997). In flooded rice production systems, dispersal of seeds by water (hydrochory) is important for many weed species and buoyancy is essential for hydrochorous seeds (Boedeltje et al., 2004). The light weight of certain weed seeds (Benvenuti, 2007; Nilsson et al., 1991) facilitates their dissemination via irrigation water in irrigated direct-seeded and transplanted systems. Barrett and Wilson (1983) found that approximately 50% of *E. crus-galli* seeds remained afloat after 4–5 days in water and speculated that water is an important dispersal agent for this species. In China also, seeds of a large number of weed species largely belonging to Poaceae, Asteraceae, and Polygonaceae families were found floating in irrigation water (Li and Qiang, 2009; Zuo and Qiang, 2008), suggesting that these weed seeds could readily disperse via irrigation directly into lowland ricefields. Weed species with floating seeds reflected the dominant weed species present in the previous crop (wheat, mustard, or rice) and, hence, included other species that are often not problematic in rice. However, when the previous crop was rice, dominant species with floating seeds included (in order of relative abundance) *F. miliacea*, *E. crus-galli*, *C. difformis*, and *Eclipta prostrata* (L.) L. Although their study did not evaluate the *movement* of seeds via irrigation water, they concluded that dispersal by water could be a significant factor for the persistence and spread of problematic rice weeds. Zuo et al. (2007) found high similarity between the soil weed seedbank in rice fields and the weed species dispersed by irrigation water as well as between the weed communities on the ridge of the paddy field and those in the ditches.

Efforts to reduce weed seed dispersal via irrigation water, particularly in lowland and flood-irrigated rice production systems, may be useful and cost-effective in preventing the spread of certain species. Practical management strategies to reduce weed seed dispersal by irrigation water may include filtering irrigation water flow at field entry points with nylon nets or collecting and removing floating weed seeds from the water surface (Li and Qiang, 2009). This might be particularly useful during the first irrigation (Zuo and Qiang, 2008) before the fields are plowed in preparation for direct seeding. Similar measures could be employed to prevent weed seed dispersal between fields as irrigation water flows between fields in majority of DSR systems.

2.2.4 Dispersal via Manure and Compost

Manure and immature compost often contain weed seeds which may be readily spread to fields (Larney and Blackshaw, 2003; Pleasant and Schlather, 1994). *Amaranthus viridis* L. seeds were reported to be dispersed by manure in upland DSR agroecosystems in the Philippines (Galinato et al., 1999). While studying the fate of *Commelina benghalensis* L. after simulated rumen digestion, Riar et al. (2010) reported the possibility of seed dispersal via ruminants. In temperate cropping systems, the commonly reported weed seeds spread by manure and compost include: *Amaranthus* *retroflexus* L., *Chenopodium album* L., *Setaria viridis* (L.) P. Beauv., *Setaria pumila* (Poir) Roem et Schult, and *E. crus-galli* (L.) Beauv. (Larney and Blackshaw, 2003; Pleasant and Schlather, 1994). However, very few studies have quantified the relative importance of this mode of dispersal in rice systems.

A long-term (4 decades) study conducted in Odisha, India, on the effects of organic and inorganic fertilizer application on weed seedbank composition, density, and diversity in the soil in a rice–rice system revealed higher weed seed density and species diversity in fields receiving farm yard manure compared to those receiving only synthetic nutrient sources (Lal et al., 2016). This study showed the significance of proper composting to ensure that weed seeds are exposed to high temperature during the process to reduce the possibility of weed seed dissemination through composted manure. The high temperature maintenance is suggested for proper composting (above 55–77°C) to assure lethal conditions for the weed seeds contained in the compost material (www.ams.usda.gov/nop). A long-term study on the rice–wheat systems in China revealed significant reductions in soil weed seedbank with the long-term application of properly composted organic fertilizers (pig manure and powder of rapeseed oil cake) (Jiang et al., 2014). More detailed studies are needed to quantify the importance of weed seed dispersal via manure compared to studies on manure effects on seed decay or seed production before drawing valid conclusions about the value of prevention. Nonetheless, several potentially valuable strategies have been suggested to limit dispersal via manure. Providing cattle with certified feeds or feeding with fodder devoid of weed seeds would reduce weed seed dissemination by cattle. Fallow fields are important grazing sources for livestock in majority of DSR-growing countries in Asia. Growing recommended fodder crops in the fallow period (Ramos et al., 2010) for feeding cattle would help minimize weed seed dissemination by livestock which, otherwise, would feed on weeds.

2.2.5 Other Modes of Dispersal

There are several other modes by which weed seeds can be dispersed in rice ecosystems but are inherently difficult to prevent. For example, some species of migratory birds including many members of the *Anatidae* are endozoochorous carriers of aquatic weed species such as those belonging to the genus *Ruppia* and *Potamogeton* (Clausen et al., 2002), with dispersal reaching as far as 300 km. Similarly, in wetlands of North America, Mueller and van der Valk (2002) found 0.3–5.2 intact seeds in feces of individual ducks (aquatic fowls) and concluded that ducks could be important agents of long-distance dispersal for some wetland weed species including Carex spp. This hypothesis does not have robust support from controlled feeding studies with *E. crus-galli* (Mueller and van der Valk, 2002).

Other modes of seed dispersal that may play an important role in promoting weed population growth include wind, insects, earthworms, and ants. Wind seed dispersal and lack of tillage were identified as factors contributing to the high invasion speed of the glyphosate-resistant *Conyza canadensis* (L.) Cronquist populations in the United States (Dauer et al., 2007). Earthworms (*Lumbricus terrestris*) have also been found to play an important role as dispersal agents for large-seeded plant species in forest and agricultural ecosystems in the United States (Regnier et al., 2008). Although their role in DSR ecosystems is unknown, it may likewise be important as earthworms are commonly observed in Asian rice soils. In different agroecosystems and geographic regions, seed dispersal by other agents including ants (Giladi, 2006) has been observed and may also play an important role in DSR.

Since weeds are often dispersed by more than one agent, no single preventive measure will be sufficient to avoid the spread of key species. For example, in Brazil, the principal weeds of irrigated rice viz. *E. crus-galli*, *Echinochloa crus-pavonis* (Kunth) Schult., *E. colona*, weedy/red rice, *Aeschynomene* spp., and *Cyperus* spp. including *C. difformis* are disseminated by irrigation water, machines, animals, wind, birds, and the rice seed (Andrade, 1982). Nonetheless, proactive management practices to prevent and minimize the dispersal of weed seeds will help lower the long-term costs of weed management in DSR.

2.3 Promoting Predation

Seed predation represents a significant avenue for weed mortality and, thus, contributes in reducing the weed seedbank (Chauhan et al., 2010; Davis et al., 2003; Gallandt, 2006; Gallandt et al., 2005; Ichihara et al., 2011; Menalled et al., 2000; Westerman et al., 2003a,b). Our knowledge on weed seed predation is insufficient in general. In DSR systems, it is important to determine the practicality of promoting predation as a means of reducing weed populations. The successful design of weed management systems that promote predation will depend on an increased understanding of potential rates of predation, the identity of specific predators, and the identification of management practices which promote predators and predation.

Most studies evaluating rates of seed predation involve placing a known number of seeds on the soil surface, recovering them after several days, and counting the percentage of seeds that have disappeared. Such studies were conducted mostly in temperate cropping systems and have demonstrated rates of seed predation from the soil surface in agricultural fields typically ranging from 10% to 93% over a period of 2–14 days, depending on weed species, season, and management system (Cromar et al., 1999; Harrison et al., 2003).

In rice cropping systems, far less information is available on weed seed predation but several studies have demonstrated that seed predation rates can be very high. In the Philippines, weed seed removal rates due to predation over a 14-day period ranged from 78% to 91% (Chauhan et al., 2010). Seed removal of *Digitaria ciliaris* Koeler was higher (93%) than that of *Eleusine indica* (88%) and *E. colona* (75%) (Chauhan et al., 2010). In India, Kumar et al. (2013) reported predation rates of 13%–39% for *C. axillaris* and 29%–71% for *E. crus-galli* over a 7-day period during the fallow period between rice harvest and planting of succeeding wheat crop. In Arkansas, USA, Bagavathiannan and Norsworthy (2013) observed weed seed predation to the level of 49%–77% in *E. crus-galli*, 36%–39% in *Ipomoea lacunosa*, 64%–75% in *Sorghum halepense*, and 80%–85% in red rice in a 5-month period. In Australia, high rates of seed predation were also observed for *Oryza meridionalis*, with the majority of seeds (75%) consumed by vertebrate predators (Wurm, 1998). Predation of seeds of several important weeds of rice and their potential predators are reported in Table 3.

Several researches have reported weed seed predation by small mammals, birds, rodents, and insects including beetles, crickets, ants, and slugs in both noncrop habitats and in agricultural systems (Best, 1983; Castrale, 1987; Gallandt et al., 2005; Manley, 1992; O'Rourke et al., 2006; Thomas et al., 1991). In Oregon, USA, Radosevich et al. (1997) reported that field mouse (*Peromyscus* spp.) consumed 99.8% of the seeds of *E. crus-galli*, *A. retroflexus*, and *C. album* from the total seed rain in an alfalfa field. In other cropping systems, birds have been reported as the most important seed predators (Navntoft et al., 2009). In annual row-crop systems in temperate climates, the carabid beetles (Coleoptera: Carabidae) are significant generalist predators (Gallandt et al., 2005; Harrison et al., 2003; Westerman et al., 2003a,b).

Table 3 Predation Rate and Predating Organism of Weed Seeds of Rice and Their Importance in Rice and Other Cropping Systems

Seed of Weed Species Predated	Site/ Location	Agricultural System/ Crop	Predating Organism	Predation Rate	Other Notes	References
Grasses						
Echinochloa colona	IRRI, Los Banõs, Philippines	Rice	Presumed to be: Invertebrates: Fire ants (*Solenopsis geminata*) and vertebrates, mainly rodents	75% in 14 days	Slightly higher in the interior of field than at field margin	Chauhan et al. (2010)
Echinochloa crus-galli	Karnal, India	Rice–wheat	Not observed	29% in CT and 71% in ZT in a week	Higher rate of seed predation in ZT system than CT	Kumar et al. (2013)
	Ontario, Canada	Corn–soybean	Ground-dwelling invertebrates including Sow bugs (Isopoda), millipedes (Myriapoda), carabids (Coleoptera), and field mice (*Peromyscus leucopus* and *P. maniculatus*)	25%–33% in ~50 days	Higher in ZT and moldboard plow than chisel plow (32 vs 24). Also relatively more in maize residue plots than in soybean and wheat residue plots	Cromar et al. (1999)
Eleusine indica	IRRI, Los Banõs, Philippines	Rice	Presumed to be: Invertebrates: Fire ants (*Solenopsis geminata*) and vertebrates, mainly rodents	88% in 14 days	Slightly higher in the interior of field than at field margin	Chauhan et al. (2010)

Panicum dichotomiflorum	Michigan, USA	Corn–soybean–wheat	Seed-eating carabid species	∼60%–90% under no-till in 5 days; ∼15%–60% under conventional tillage at five sampling timings	Activity densities of seed-predating carabid species were over three times higher in the no-till compared to the conventional and organic systems. Also, predation was >2 times higher in no-till than in conventional and organic systems	Menalled et al. (2007)
	Michigan, USA	Maize	Vertebrates + invertebrates	Predation in spring was not significant but occurred during overwinter	No effect of position (near edge vs interior)	Marino et al. (1997)
Digitaria ciliaris	IRRI, Los Banõs, Philippines	Rice	Presumed to be: Invertebrates: Fire ants (*Solenopsis geminata*) and vertebrates, mainly rodents	93% in 14 days	Slightly higher in the interior of field than at field margin	Chauhan et al. (2010)
Digitaria sanguinalis	Michigan, USA	Maize	Invertebrates + vertebrates	13% day^{-1}	More predation in complex landscape than simple landscape. More predation by invertebrates than vertebrates	Menalled et al. (2000)
		Laboratory study	Field cricket (*Gryllus pennsylvanicus*)	69 and 87 seeds in 24 h by male and female *G. pennsylvanicus*, respectively	No choice lab study	Carmona et al. (1999)

Continued

Table 3 Predation Rate and Predating Organism of Weed Seeds of Rice and Their Importance in Rice and Other Cropping Systems—cont'd

Seed of Weed Species Predated	Site/ Location	Agricultural System/ Crop	Predating Organism	Predation Rate	Other Notes	References
Broadleaved						
Eclipta alba	Karnal, India	Rice–wheat	Not observed	29% in CT and 71% in ZT in a week	Higher rate of seed predation in ZT system than CT	Kumar et al. (2013)
Amaranthus retroflexus	Michigan, USA	Maize	Vertebrates + invertebrates	In Spring, predation was significant but not during overwinter	No effect of position (near edge vs interior)	Marino et al. (1997)
	Michigan, USA	Maize	Invertebrates + vertebrates	12% day^{-1}	More predation in complex landscape than simple landscape. More predation by invertebrates than vertebrates	Menalled et al. (2000)
	Maine, USA	Vegetable-based rotation	Ground carabid beetle (Harpalus rufipes) + vertebrates; invertebrates were dominant	>40% in 4–11 days		Gallandt et al. (2005)
	North Carolina, USA	Soybean; Maize; Hey	(Coleoptera: Carabidae)	Least square mean removal rate was 0.32–1.05 seeds per 2-week	Field border type (different vegetation) did not affect seed predation	Fox et al. (2013)
	North Carolina, USA	Soybean	Invertebrates (carabid beetles, ants, crickets) + vertebrates (mice)		Two times higher seed predation in ZT than in conventional tillage	Brust and House (1988)

	Presque Isle, Maine	Potato	*Harpalus rufipes* (Coleoptera: Carabidae)		Presence of *H. rufipes* larvae reduced the emergence of *A. retroflexus* from 0 to 3 cm depth but emergence was not affected by the presence of predator when seeds were below 3-cm soil depth. This shows that larvae stage of carabid beetles can also consume buried seeds	Hartke et al. (1998)
		Laboratory study	Field cricket (*Gryllus pennsylvanicus*)	90 seeds and 223 seeds in 24 h by male and female *G. pennsylvanicus*, respectively	No choice lab study	Carmona et al. (1999)
		Fallow land	Fire ant (*Solenopsis invicta* Buren)			Seaman and Marino (2003)
Caesulia auxillaris	Karnal, India	Rice–wheat	Not studied	13% in CT and 39% in ZT in a week	Higher rate of seed predation in ZT system than CT	Kumar et al. (2013)
Sedges						
Cyperus rotundus	Costa Rica	Field study	Larvae of a billbug		Not reported as a pest on cultivated crops and, hence, is considered as biocontrol agent	Neeser et al. (1997)

In rice fields, both vertebrates and invertebrates consume weed seeds, with ants identified as particularly important predators in several studies. In Southeast Asia, ants feed on *Paspalum conjugatum* seeds (Waterhouse, 1994) and fire ants (*Solenopsis geminata*) do the same in Mexico (Carroll and Risch, 1984). In the Philippines, both invertebrates (fire ants) and vertebrates (rodents including the Asian house rat *Rattus tanezumi*) have been reported as weed seed predators in rice fields, with fire ants as the main predators and rodents as secondary predators (Chauhan et al., 2010; Miller et al., 2008; Way et al., 2002). In Japan, in wheat fields converted from paddy fields, invertebrates (crickets and ground beetles) were the main predators of *Lolium multiflorum* Lam. in the boundary strips while both vertebrates (rodents or birds) and invertebrates (crickets and ground beetles) were the predators in the field interior areas (Ichihara et al., 2011).

Weed seed predation can be affected by many factors including site (Honek et al., 2003); crop (Heggenstaller et al., 2006; Westerman et al., 2005); season (Heggenstaller et al., 2006; Holmes and Froud-Williams, 2005); fallow vegetation (Gallagher et al., 1999); the amount and kinds of weed seeds (Risch and Carroll, 1986); tillage (Brust and House, 1988); quantity and quality of crop residue in zero-till system (Cromar et al., 1999); vegetation cover (Meiss et al., 2010); seed demand by predators (Seaman and Marino, 2003); microsite predator density, the timing of seed dispersal, and seed residence time on the soil surface (Westerman et al., 2006); herbicides and fertilizers used in the system (Hance, 2002); microenvironment of the habitat (Saska et al., 2010); total number (Menalled et al., 2000) and diversity of predators (Gaines and Gratton, 2010); the activity density of predators (O'Rourke et al., 2006); seasonal variation in predator physiology and feeding preferences (Honek et al., 2006); distance from field edge (Booman et al., 2009; Jacob et al., 2006; Saska et al., 2008) and bordering vegetation (Diaz, 1992); weed species (Muñoz and Cavieres, 2006; Willson and Whelan, 1990); depth of seed burial (Rodríguez and Garcia, 2009); water management (Ward, 2008); and insecticide use (DiTommaso et al., 2014).

In general, surface residue or vegetation has been shown to be an important factor promoting predation. For example, Puricelli et al. (2005) suggested that the major factors influencing seed predation in zero-tillage wheat/soybean rotation were the higher crop residue levels which provided a favorable habitat for seed predators. Shelter is crucial for hiding from predators and affects predator behavioral decisions such as microhabitat choice, feeding activity, and movement (Lima and Dill, 1990). Vegetation cover has been reported to increase the number of predators and the rates of weed seed predation in several studies (Heggenstaller et al., 2006; Navntoft et al., 2009). Davis and Liebman (2003) found higher rates of predation and caught more seed predators in fields with red clover cover crops compared to bare soil. In contrast, Bagavathiannan and Norsworthy (2013) in the midsouthern United States did not find any effect of vegetation cover (rye cover crop) on the acceleration of weed seed predation. A greater abundance of fire ants was observed under killed crop cover mulch (Pullaro et al., 2006). Higher predation rates along edges of crop fields and near bordering vegetation may also reflect the predators' need for shelter from higher-level predators (Holmes and Froud-Williams, 2005; Jacob et al., 2006). In the rice–wheat rotation in India, Kumar et al. (2013) reported a higher postdispersal seed predation of rice weeds including *E. crus-galli* (71% vs. 29%) and *C. axillaris* (39% vs 13%) under ZT with residue than under conventional till system during a 1-week period between rice harvest and planting of succeeding wheat.

The rice–duck farming (RDF) systems of East Asia are believed to control weeds effectively (Li et al., 2012) as the ducks eat the weeds and grass seeds (Men et al., 1999). In an experiment conducted for 9 years under RDF, Li et al. (2012) observed a decline from 38 to 21 weed species in the weed seedbank and more than 90% reduction in the densities of seeds in the weed seedbank and in the weed biomass. This evidence indicates that the RDF system has potential as a weed management approach for weed seedbank depletion.

Seed depth is one of the most important factors determining the rates of seed predation. Although larval stages of carabids have been shown to consume buried weed seeds (Hartke et al., 1998), most seed predation is thought to occur at or near the soil surface (Saska, 2004). When weed seeds are buried even a few centimeters in the ground, they are much less susceptible to predation and predation rates decline drastically with increase in burial depth (Rodríguez and Garcia, 2009). Practices such as ZT which minimize soil disturbance and, hence, weed seed burial might therefore enhance seed predation by increasing the time that seeds spend on the soil surface for predation.

Tillage is a factor that often influences seed predation rates as it is thought to reduce rates of predation by disturbing habitats of soil-borne predators and by protecting seeds through burial. Conversely, ZT systems may increase seed predation since weed seeds are left on the soil surface and the period of weed seed exposure is extended (Baraibar et al., 2009; Holland, 2004; Westerman et al., 2006). Reduced tillage may also indirectly increase predation by facilitating the retention of surface residues that provide shelter for predators. For example, in the United States, doubled weed seed predation rates were observed in no-till than in moldboard plow fields (Brust and House, 1988). Diaz (1991) observed that tillage, in particular moldboard plowing, can damage the nests of harvester ants. In temperate cropping systems, both the abundance and diversity of carabid beetles were reduced following tillage (Kromp, 1999; Purvis and Fadl, 2002) through a decrease in the availability of suitable prey and alternative food sources (Brust, 1990a,b).

Although tillage is often cited as detrimental to seed predators and rates of predation compared to ZT (Brust and House, 1988), it is not always the case (Brainard et al., 2013; Cardina et al., 1996). In some cases, CT has resulted in greater rates of predation than no-tillage with a high activity density of predators like *Pterostichus melanarius* found in disturbed systems (Shearin et al., 2007). Cromar et al. (1999) also observed a nonlinear relationship between the level of disturbance and predation and concluded that other factors, such as the mobility of invertebrates and food availability, play equally important roles in determining seed predation rates.

Irrigation practices may also influence seed predators and rates of predation. Flooding creates unfavorable conditions for ant colonies (Meeson et al., 2002). In the semiarid cropping systems of Spain, Baraibar et al. (2009) reported that irrigation in a semiarid cereal production system results in the elimination of granivorous harvester ants (*Messor* spp.), which are otherwise common in arid and semiarid regions around the world. On the other hand, winter flooding of rice fields in Italy is known to promote an increase in bird species which may play important roles in the predation of weedy rice (Fogliatto et al., 2010). However, the impact of irrigation practices on predators in rice cropping systems in Asia has not been extensively studied. It is likely that the predators differ in their responses to the water management practices used in DSR-based cropping systems, depending on their habitat requirements and activity patterns (Diaz, 1991; Loman, 1991).

2.3.1 Identification of Predators and Strategies That Conserve Them

The major determinants of seed predation rates are space, time, and habitat (Birthisel, 2013). Seed predators and predation rates were known to be affected by habitat. For example, ants preferentially forage in open areas (Hulme, 1997) while small mammals (Kelt et al., 2004) and carabids (Diehl et al., 2012) typically prefer vegetative cover. A positive correlation was found between vegetative cover and seed predation by vertebrates and invertebrates in agricultural fields (Meiss et al., 2010), which could be attributed to the avoidance behavior of predators (Kelt et al., 2004) or to favorable microclimates that vegetation cover provides (Diehl et al., 2012).

Identification and encouragement of management strategies that conserve populations of beneficial predators may have important benefits for weed suppression (Cromar et al., 1999). Such strategies include the establishment of field edge or bund vegetation (Baraibar et al., 2011; Gallandt et al., 2005; Thorbek and Bilde, 2004; Way and Heong, 1994, 2009); retention of crop residue in rotational crops (Kumar et al., 2013); reductions in tillage and delay in tillage in the fallow period (Brust and House, 1988; Chauhan et al., 2010; Holland, 2004; Kumar et al., 2013); increasing compost mulching (Mathews et al., 2004); reduction in pesticide use in rotational crops (DiTommaso et al., 2014); and changes in the duration and timing of flooding (Fogliatto et al., 2010; Way and Heong, 2009).

2.3.1.1 Maximize Seed Exposure Through Changes in Tillage and Irrigation Timing

In DSR systems in Asia, after the rice is harvested, the fields are often kept fallow with minimal soil disturbance: (a) during the next season under rainfed situations or (b) until the next crop under irrigated conditions. Under such conditions, weed seeds shed during the crop season remain on or near the soil surface where they may be very susceptible to predation. Zero-tillage in subsequent crops (e.g., wheat) extends the period during which these weed seeds remain near the soil surface and are susceptible to predation, and may result in fewer weed seeds when the rotation returns to rice. Chauhan and Johnson (2010) suggested that crop management practices such as zero-till or delayed tillage could increase the exposure of weed seeds to predators (ants, beetles, etc.).

2.4 Promoting Decay

The persistence of weed seeds may be strongly influenced by agronomic practices in DSR systems, which in turn affect agents of seed decay like soil microbes (Kennedy, 1999; Kremer, 1993; Schafer and Kotanen, 2003). Understanding the interactions between seeds and the factors influencing seed decay may have important implications for future weed management systems targeting seedbanks (Chee-Sanford et al., 2006; Gómez et al., 2014). However, information on factors influencing weed seed decay in the soil is meager in general, more particularly in DSR systems.

Changes in the weed seedbank density over time (in the absence of seed production) can be described by "rates of decay," although this often includes not only losses due to microorganisms and physiological death but also losses due to fatal germination and seed predation. In seed burial studies, seeds are buried in mesh bags which exclude seed predators and their persistence is monitored over time. Such studies assess both decay and fatal germination. Despite their limitations in determining the mechanisms of persistence, they provide indications as to the rates of decline of seed viability and the potential role of microbial decay.

Normally, total seedbank densities decrease exponentially with time with half-life varying by species (Barralis et al., 1988; Wilson and Lawson, 1992). Often, but not always, seed persistence is lower for (i) annual grass species compared to annual broadleaf species; (ii) species with weak dormancy mechanisms compared to those with strong dormancy; and (iii) species with large or elongated seeds compared to those with small and round seeds (Mohler, 2001). For example, in the US Corn Belt, the persistence of weed seedbanks of broadleaf weeds such as *C. album* and *Abutilon theophrasti* was 52%–60%, whereas for *Setaria faberi*, a grass weed, it was only 21%–22% after 1 year of burial (Davis et al., 2005). The viability of the seeds of the grasses (*Avena fatua* L. and *Hordeum jubatum* L.) was reduced to $<1\%$ whereas the viability of 13 annual broadleaf weeds tested was 32% after 3.7 years (Conn and Deck, 1995). However, within these broad categories, seeds vary considerably in their susceptibility to decay based on other characteristics including seed coat thickness (Gardarin et al., 2010), biochemical constituents such as orthodihydroxyphenols (Davis et al., 2008), desiccation tolerance and degree of water permeability of the seed coat (Norton et al., 2004), the carbon-to-nitrogen (C:N) ratio of the seed (Chee-Sanford et al., 2006), and antimicrobial or deterioration resistant compounds (Hendry et al., 1994; Kremer, 1986) in the seed coat.

Limited information is available on the longevity of rice weed seeds and the factors influencing their persistence or rates of decay. Seeds of weeds in rice buried in nylon mesh bags in a long-term study in Haryana, India, showed that only 4%, 16%, 23%, and 35% of the seeds of *E. crus-galli*, *C. iria*, *C. axillaris*, and *Dactyloctenium aegyptium* Willd., respectively, remained viable after 2.5 years of burial at 10 and 20 cm soil depths (Kumar et al., unpublished data). These results conform to the general relationships between seed characteristics and persistence summarized by Mohler (2001). The large seeds of the grass *E. crus-galli* had shorter persistence compared to both a smaller-seeded grass (e.g., *D. aegyptium*) and a broadleaf species with similar seed size (*C. axillaris*). Egley and Chandler (1978) also observed in their seed longevity study at Mississippi, USA, that $<$1% of the seeds of *E. crus-galli* remained viable after 2.5 years of burial in the soil. Noldin et al. (2006) studied the longevity of red/weedy rice in Texas and found only 1% viable seeds when buried at 0 cm depth and 0%–12% when buried at 12 cm depth after 1 year.

Decay of weed seeds in the soil may occur due to: (i) microbes (Chee-Sanford et al., 2006; Kennedy, 1999; Kremer, 1993; Schafer and Kotanen, 2003) or (ii) aging and senescence (Priestley, 1986). Soil-borne microorganisms such as bacteria, fungi, and viruses can cause seed decay either alone or in combination with other mechanisms of seed death (Davis and Renner, 2007; Kremer, 1993; Kumar et al., 2011).

Rates of fungi-mediated decay are sometimes estimated by comparing the persistence of fungicide-treated and untreated weed seeds. Such studies demonstrate that fungi sometimes play an important role in seed decay. For example, fungicide treatment increased the persistence of the seeds of *Amaranthus powellii* S. Wats. (Powell amaranth) by as much as 25.5% and of *E. crus-galli* by as much as 12% (Kumar et al., 2011). Similar results have been found for other weed species including black medic (*Medicago lupulina* L.), field bindweed (*Convolvulus arvensis* L.), and birdsfoot trefoil (*Lotus corniculatus* L.) (Leishman et al., 2000). However, fungicide treatment had a relatively small effect on the longevity of the highly dormant *A. fatua* seeds (Gallandt et al., 2004).

Environmental factors influencing seed decay include soil moisture (Chantre et al., 2009), temperature (Fogliatto et al., 2010), gas exchange (Davis et al., 2008), and soil nitrogen content (Kumar et al., 2011). Among these, the effect of soil moisture on seed persistence is perhaps best documented, for example winter flooding of rice fields in Italy greatly reduced the persistence of weedy rice (Fogliatto et al., 2010). The authors showed that the viability of weedy rice seeds was reduced under moist conditions and concluded that seed decay was at least partly responsible for the observed reductions in seed persistence under winter flooding. However, exposure to dry condition (lower rainfall/moisture) can enhance seed persistence for species tolerant to desiccation (Burnside et al., 1996) but can reduce the persistence of other species (Tweddle et al., 2003). Schafer and Kotanen (2003) observed that the risk of loss of seeds due to fungal attack was greater in wet soils than in dry soils and that seed decay by fungi increased as soil moisture increased.

Since soil-borne microorganisms are often more active in the top layers of the soil (Swanton and Booth, 2004), decay often occurs more rapidly in the surface layers. For example, while studying the seed longevity of *E. colona* in rice fields in Costa Rica, Chaves et al. (1997) observed that seeds placed on the soil surface persisted for less than 4 months while buried seeds had 34% persistence after 10 months. They speculated that seed decay rather than in situ germination or predation was responsible for the greatest reduction in seed persistence. Similarly, the persistence of *E. colona*, *Urochloa panicoides* P. Beauv., and *Hibiscus trionum* L. increased significantly with burial depth (Walker et al., 2010). *Datura stramonium* L., whose seeds survived after 34 years at 34-cm depth burial, decayed faster when the seeds were in the upper layers (2.5–10 cm) of the soil (Stoller and Wax, 1974; Toole and Brown, 1946). The seed decay of *Bidens pilosa* L. (Carmona and Boas, 2001) and *Sonchus oleraceus* L. (Chauhan et al., 2006b) was also greater on the soil surface. Faster rates of decay by weed seeds on the soil surface have also been attributed to their exposure to greater fluctuations in environmental conditions that may promote decay (Taylorson, 1970). Alternatively, conditions on or near the soil surface may break dormancy, resulting in seed losses via germination, which may be mistakenly attributed to decay.

Hypothesized strategies to enhance seed decay include changes in the type and timing of tillage (Chauhan and Gill, 2014; Noldin et al., 2006; Swanton and Booth, 2004), irrigation (Fogliatto et al., 2010; Hosoi et al., 2010), and soil amendments including composts and cover crops (Fennimore and Jackson, 2003; Kumar et al., 2011). Such strategies may either promote indigenous natural microflora, with the potential to selectively promote weed seed decay (Chee-Sanford et al., 2006) or to place seeds in closer proximity to decay agents (Gallandt et al., 1999).

2.4.1 Manipulating Tillage to Promote Decay

Tillage can have a major impact on changes in seedbank density, but both the magnitude and direction of tillage effects can vary enormously among species and cropping systems. Since seed decay, like seed predation, is usually more rapid on the soil surface, noninversion tillage, or no-till may result in greater rates of weed seed decline. Chauhan et al. (2006a) reported higher rates of seed decay in no-till than in minimum tillage (48%–60% vs 12%–39%). In contrast, in temperate cropping systems, Gallandt et al. (2004) did not find any difference in the seed decay of *A. fatua* under conventional and no-till systems in a 10-month burial period. These inconsistent results suggest the need for more research to quantify the effects of tillage on weed seed persistence in rice-based systems. Also in a seed burial study in India, under the rice–wheat cropping systems, the persistence of rice weed seeds was not affected by tillage (Kumar et al., unpublished data).

2.4.2 Impact of Soil Amendments

Organic amendments such as cover crops or compost may also influence weed seed decay by altering soil microbial communities. For example, Fennimore and Jackson (2003) observed reduction in seedbank of *Capsella bursa-pastoris* (L.) Medicus over a 24-month period in the plots with organic amendment than in the nonamended plots. They also observed higher microbial biomass in organic amended plots and found negative correlation between *C. bursa-pastoris* emergence and microbial biomass. By comparing the persistence of fungicide-treated and untreated seeds in cover crop amended and nonamended soils, Kumar et al. (2011) found that fungal pathogens can play an important role in the mortality of weed seeds such as *E. crus-galli*, but that the rate of fungal-mediated decay did not vary with cover crop treatment. However, potential cover crop-mediated changes in soil microbial communities affecting seed persistence have not been extensively explored—especially in rice cropping systems—and may provide important clues to the management of the weed seedbank. Weed seed decay and soil microbial communities especially fungal and bacterial communities were significantly correlated, while there was no correlation between weed seed decay and soil C:N ratio or texture, which indicates the possibility of enhancing weed seed decay by manipulating soil microbial communities (Davis et al., 2006).

2.4.3 Irrigation Management

Irrigation management can have a major impact on soil microorganisms and potential agents of seed decay, since the abundance of these agents depends critically on levels of soil moisture. Moisture management during fallow periods and in rotational crops may be particularly valuable in managing weedy rice (Fogliatto et al., 2010), but this approach has not been studied for DSR systems in Asia. Hosoi et al. (2010) also reported an accelerated death of shattered weedy rice seeds on the soil surface due to exposure to cold temperatures during winter. However, very little information is available to understand and manipulate irrigation strategies to suppress weed seeds through decay.

2.5 Promoting Fatal Germination

If all weed seeds could be induced to germinate at the same time, weed management would be simpler. Unfortunately, weed seeds are capable of remaining in the soil seedbank for many years and a large variation in germination timing both between and within species makes management challenging. Nonetheless, knowledge of factors influencing seed dormancy and germination can be exploited to help manage weeds through two general strategies: (1) stimulate weed seed germination and kill emerged weeds before planting the crop or (2) inhibit weed seed germination during the period of crop establishment. The latter approach has been discussed in detail in previous reviews and includes practices during rice cultivation such as reduced tillage, use of preemergence herbicides, mulching, intersowing with sesbania, and flooding (Chauhan, 2012a,b; Kumar et al., 2013; Rao et al., 2007). The former approach has received less detailed attention, but is a potentially valuable tool for preventive weed management in rice cropping systems. It includes practices that are purposely designed to stimulate the fatal germination of weeds (e.g., stale seedbed practices) as well as those that may stimulate fatal germination while simultaneously accomplishing other agricultural goals (e.g., crop rotation).

2.5.1 Stale Seedbed

The "stale" or "false" seedbed approach involves two distinct phases: (1) stimulating the germination of weeds and (2) killing weeds prior to crop establishment. In the "stimulation phase," the optimal timing and method of stimulation (e.g., tillage or irrigation) is likely to depend on the weed species present, their dormancy status, and knowledge of edaphic factors which stimulate germination. Likewise, in the "termination stage," the optimal tactic (e.g., herbicides, tillage, and flooding) to kill weeds will depend on which weed species are present as well as the impact of these practices on subsequent weeds and the crop.

2.5.1.1 Seed Dormancy and the Timing of Germination Stimulation

The optimal timing to stimulate germination for stale seedbeds is a critical issue that has received relatively little attention. Attempting to stimulate the germination of weed seeds when the majority are either dormant or quiescent (e.g., due to suboptimal temperatures) is futile. Likewise, delaying germination stimulation until the majority of weeds are nondormant may be risky if weeds do not germinate rapidly enough to be killed before crop planting. Therefore, knowledge of the nature of seed dormancy in target weeds and their germination periodicity may be important for optimizing stale seedbed and similar practices. In particular, knowledge of the timing of dormancy release, peak timing of germination, and the factors which stimulate germination may suggest strategies for promoting the fatal germination of weed seeds.

Most of the major weed species of rice have nondormant seeds (ND) or have physiological (PHY) or physical (PD) seed dormancy, although some species have multiple mechanisms of dormancy (Table 4). Seed dormancy is a barrier to seed germination under conditions (e.g., temperature, moisture) that would normally be favorable (Grundy, 2003). Nondormant seeds can germinate over a wide range of temperatures and moisture conditions. Seeds with physiological dormancy will either not germinate or germinate only over a very narrow range of conditions at maturity. In contrast, seeds with physical dormancy fail to germinate largely due to the impermeability of the seed coat to water. For such seeds, dormancy is generally released through abrasion of the seed coat and is irreversible. The perennial weed flora has developed numerous strategies to overcome seasonal dryness, heat, and other environmental conditions. One such strategy is exhibition, by many species, of complete annual dieback to summer dormant perennating structures such as shoot buds, bulbs, corms, stem tubers, or root tubers (Pate and Dixon, 1982).

Nondormant seeds are good candidates for stale seedbed practices since they may be induced to germinate days to months before rice cultivation depending only on the temperature and moisture conditions. Rice weeds with seeds that are reported to have little or no dormancy include *E. prostrata*, *C. difformis*, *F. miliacea*, and *Euphorbia hirta* (Table 4).

Seeds with physical or physiological dormancy may not always be induced (depending on the age of the seeds in the seedbank) to germinate until much closer to the time of rice planting; hence, are less susceptible to stale seedbeds compared to nondormant seeds. Common rice weeds with physiological dormancy include *Amaranthus spinosus*, *E. indica*, *E. colona*, and *I. rugosum*. (Table 4). Seeds with physiological dormancy generally are dormant at the time of seed shed with the timing and extent of dormancy release controlled by complex interactive effects of environmental factors including temperature and moisture. Physiological dormancy is usually characterized by physiological inhibiting mechanisms of the embryo (e.g., impermeability to oxygen; inhibitors) that prevent emergence of the radical (Baskin and Baskin, 2001; Benvenuti and Macchia, 1995). Release of physiological dormancy of most

Table 4 Rice Weeds With Types of Seed Dormancy and Factors Which Can Help in Releasing Dormancy

Species	Dormancy	Dormancy Broken by	References
Grasses			
Echinochloa crus-galli	PHY	Scarification; dormancy declines gradually with storage time	Song et al. (2015), Soerjani et al. (1987a,b), Benvenuti et al. (1997), and Honek and Martinkova (1992)
Echinochloa colona	PHY	Scarification; potassium nitrate treatment; storage in light and dark; fluctuating temperature	Popay (1973), Dubey (2004), Holm et al. (1997), Chun and Moody (1985), and Galinato et al. (1999)
Echinochloa glabrescens	Yes	Pretreatment of seeds either by soaking in nitric acid (0.1 N) for 1 day or removal of the hull	Kim and Moody (1989a,b)
Leptochloa chinensis	PHY or ND (no dormancy)	Light and moisture	Matsuo and Kataoka (1983), Galinato et al. (1999), and Chauhan and Johnson (2008a)
Dactyloctenium aegyptium	PHY	Alternate temperature of 35°/23° ± 3.5°C for 8/16 h; mechanical rubbing and presoaking for 10 days	Popay (1973) and Saeed and Sabir (1993)
Eleusine indica	PHY	Light or scarification; alternating temperatures; after ripening period of 3 months improves germination	Popay (1973), Galinato et al. (1999), and Chauhan and Johnson (2008e)
Ischaemum rugosum	PHY	Scarification and light	Holm et al. (1997) and Galinato et al. (1999)
Rottboellia exaltata	PHY	Periodic wetting; wetting and drying in light	Popay (1973) and Thomas and Allison (1975)

Table 4 Rice Weeds With Types of Seed Dormancy and Factors Which Can Help in Releasing Dormancy—cont'd

Species	Dormancy	Dormancy Broken by	References
Digitaria ciliaris	PHY or very low dormancy	Alternating temperatures, scarification, and exposure to light	Holm et al. (1997), Galinato et al. (1999), and Chauhan and Johnson (2008f)
Digitaria longiflora	Very low dormancy	Exposure to light	Chauhan and Johnson (2008f)
Paspalum distichum	PHY	Light and temperature	Huang and Hsiao (1987)
Paspalum conjugatum	PHY	Light	Galinato et al. (1999)
Paspalum scrobiculatum	PD	Mechanical or acid scarification	Galinato et al. (1999)
Cynodon dactylon	PHY		Moreira (1975)
Broadleaves			
Eclipta prostrata	ND		Ramakrishnan (1960), Lee and Moody (1988b), and Chauhan and Johnson (2008c)
Portulaca oleracea	PHY		Popay (1973), Kruk and Arnold (1998), and El-Keblawy and Al-Ansari (2000)
Trianthema portulacastrum	PHY		Mohammed and Sen (1990)
Amaranthus spinosus	PHY	Light + IAA, ascorbic acid	Vyas and Shrimal (1974)
Ageratum conyzoides	ND (Sauerborn, 1985), PHY (Popay, 1973)	Alternating temperatures; potassium nitrate with light	Popay (1973) and Ikeda et al. (2008)
Commelina benghalensis	PHY	Scarification; clipping off the seed coat; chemical (concentrated sulfuric	Popay (1973), Budd et al. (1979), Walker and Evenson (1985),

Continued

Table 4 Rice Weeds With Types of Seed Dormancy and Factors Which Can Help in Releasing Dormancy—cont'd

Species	Dormancy	Dormancy Broken by	References
		acid [H_2SO_4] and sodium hypochlorite [NaOCl]) and dry heat and hot water treatments to crack the seed coat. Concentrated sulfuric acid and NaOCl were more effective than dry heat and hot water	Kim et al. (1990), and Galinato et al. (1999)
Commelina diffusa	PD		Watanabe and Hirokawa (1975)
Euphorbia hirta	ND		Galinato et al. (1999)
Sphinoclea zeylanica	PHY	Light	Mercado et al. (1990)
Corchorus olitorius	PD	Scarification by concentrated H_2SO_4 for 60 min or with emery cloth or seed coat cracking	Chauhan and Johnson (2008b) and Chavan and Trivedi (1962)
Mimosa invisa	PD		Felippe and Polo (1983)
Aeschynomene indica	PHY	Scarification; burial in dry condition	Baskin and Baskin (1998) and Fukumi and Nakata (2008)
Celosia argentia	PHY	GA	Vyas and Shrimal (1974)
Monochoria vaginalis	ND (Kim and Moody, 1989a,b), PHY (Chen and Kuo, 1999)	Light and temperature	Kim and Moody (1989a,b) and Chen and Kuo (1999)
Sedges			
Cyperus difformis	ND	Light requirement for germination is completely overcome by 2-week of cold	Kim and Moody (1989a,b) and Derakhshan and Gherekhloo (2013)

Table 4 Rice Weeds With Types of Seed Dormancy and Factors Which Can Help in Releasing Dormancy—cont'd

Species	Dormancy	Dormancy Broken by	References
		stratification. With cold stratification, seeds can germinate also in darkness	
Cyperus iria	Low level of primary dormancy	One month after ripening period; light stimulates germination; seed burial in upland soil can enhance seed germination in darkness. It can enter into secondary dormancy if stored in darkness at low temperature or in submerged soil	Chozin and Nakagawa (1988)
Cyperus rotundus		Cultivation; apical dominance in tubers—at least 7 years	Parsons and Cuthbertson (1992)
Fimbristylis miliacea	ND		Kim and Moody (1989a,b)
Scirpus juncoides	PHY	Wet soil and low temperate	Watanabe et al. (1991)

rice weeds is promoted by cool wet conditions and is characterized by a widening of the range of temperatures over which germination will occur (Benech-Arnold et al., 2000). For these species, stale seedbed practices must be delayed sufficiently for substantial dormancy release to occur and efficacy may be limited unless rice planting is also delayed.

Rice weeds with physical dormancy include *C. diffusa*, *C. benghalensis*, *Corchorus olitorius*, *Mimosa invisa*, and *M. pudica* (Table 4). For such species, hard seed coats often contribute to dormancy and persistence in the soil (Egley and Chandler, 1983). Promoting the germination of seeds with physical dormancy generally requires breaking the impermeable layers of the seed coat to allow the entry of water. The seed of *M. pudica* has a hard seed coat which needs to be scarified, or exposed to heat, to stimulate germination (Chauhan and Johnson, 2009b). For weeds with physical dormancy, the mechanisms by which dormancy is broken are poorly understood for many weed species, but can involve high fluctuating temperatures, fire, low temperatures, microbial action, and passage of seeds through the digestive systems of animals (Baskin and Baskin, 2001). Intraspecific variation in seed coat thickness combined with microsite variation in factors that promote scarification result in a wide variation in the dormancy status of seeds with physical dormancy. For such species, the efficacy of stale seedbeds will be limited since many seeds are likely to be dormant at any given time.

2.5.1.2 Seed Quiescence and the Optimal Type of Germination Stimuli

The optimal method of stimulating the germination of weed seeds—and, hence, the efficacy of stale seedbeds—will vary by species and will depend not only on the dormancy status of the seeds but also on factors enforcing quiescence. Quiescent seeds are not truly dormant but do not germinate because environmental factors are not suitable for germination. Temperature, moisture, light, and nutrient conditions are particularly important determinants of germination of quiescent seeds of many rice weeds. Manipulating these factors may improve the efficacy of stale seedbed practices.

Temperature is generally considered the most important determinant of germination for nondormant/quiescent seeds (Garcia-Huidobro et al., 1982). Since rice is a warm season crop, most weeds of rice have relatively high base temperatures for germination and have very limited germination until optimum temperatures for germination are reached. For this reason, the efficacy of stale seedbeds is likely to be greater during warm periods preceding rice establishment and may be very poor if unseasonably cool temperatures prevail. On the other hand, weed seeds with hard seed coats have been reported to be relatively insensitive to temperature. For example, scarified seeds of *M. invisa*, *C. olitorius*, and *Melochia concatenate* were found to germinate equally well over a wide range of alternating temperatures (25/15 to 35/25°C alternating day/night temperatures) (Chauhan and Johnson, 2008b). Therefore, depending on the status of scarification and moisture, the seeds of these species may be induced to germinate even under relatively cool conditions.

Light is another well-known stimulant of many weeds of rice, particularly those having physiological dormancy (Table 4). Rice weeds with seeds that are strongly affected by light include *C. difformis*, *C. iria*, *F. miliacea*, *Digitaria longifolia*, *D. ciliaris*, *L. chinensis*, *E. colona*, *E. crus-galli*, *E. prostrata*, *Chromolaena odorata*, *Tridax procumbens*, *Celosia argentea*, *Portulaca oleracea*, and *Ludwigia hyssopifolia* (Chauhan et al., 2010). For these species, exposure to light for even a very short duration is often sufficient to initiate the biochemical processes that result in germination (Chen and Kuo, 1999). For these species, tillage is often an effective method for stimulating germination since it typically results in sufficient light exposure. In contrast, seeds of several important weeds of rice are insensitive to light and, therefore, tillage is less likely to stimulate their germination. Under this category are most weeds with physical dormancy (e.g., *C. olitorius*) as well as many weeds in the Fabaceae family like *M. invisa* (Baskin et al., 1998; Silveira and Fernandes, 2006). Similarly, seeds of *R. cochinchinensis* and *Sida rhombifolia* L. can germinate equally in light and dark (Galinato et al., 1999; Thomas and Allison, 1975).

Adequate soil moisture is a prerequisite for the germination of all weed species. Therefore, in cropping systems in which there is low rainfall prior to rice planting, irrigation may be necessary to stimulate seed germination. Indeed, in most studies examining stale seedbeds in rice systems, presowing irrigation rather than tillage is used to stimulate a flush of weeds which are thereafter killed with nonselective herbicides or cultivations (Kumar et al., 2013; Singh et al., 2009). Preventive weed management using the combination of stale seedbed preparation and destruction of the rest of the emerged weed seedlings by submerging them under water for 10 days was also reported (Sindhu et al., 2010).

In stale seedbeds in temperate regions, tillage is the primary method for stimulating preplanting germination of weeds. Tillage is known to stimulate the germination of many weed species through the combined effects of different mechanisms including soil aeration, exposure of seeds to light, and increased N mineralization and soil temperature (Mohler, 2001). In this approach, seedbeds are prepared several weeks prior to crop planting using standard tillage practices. Because tillage generally stimulates weed germination, a flush of weeds emerges and is terminated prior to crop planting to reduce the seedbank and the subsequent weed emergence in the crop (Bond and Grundy, 2001; Gallandt, 2006).

Although tillage and irrigation are strong candidates for promoting weed germination in stale seedbeds, other approaches may warrant additional study in rice. For example, Foley (2001) suggested engineering soil microorganisms that produce germination-stimulating substances to stimulate or inhibit weed seed germinability. In the United States, injection of ethylene gas was used to stimulate the germination of *Striga asiatica*, which subsequently died in the absence of a host plant (Eplee, 1976).

Another approach that has shown promise in research trials involves combining stale seedbeds with floating row covers (made of spun bonded polypropylene fabric) which can stimulate weed germination through higher soil temperature and moisture. Brainard et al. (2007) found that floating row covers in combination with stale seedbeds reduced the subsequent emergence of *P. oleracea* by over 90%. However, the practicality and cost effectiveness of these approaches in rice cropping systems have not been demonstrated.

As N and other nutrients are known to stimulate the germination of many weed species (Lundy et al., 2010; Nagy and Nádasy, 2011), changes in the timing or rate of N fertilizer applications or adjustments in the timing of practices which influence soil N dynamics (e.g., tillage; cover crop incorporation) have also been suggested as a means of stimulating weed germination (Hurtt and Taylorson, 1986; Lundy et al., 2010) to enhance stale seedbed efficacy. Nitrogeneous compounds including both nitrate and ammonium salts are perhaps best known for their ability to stimulate seed germination (Baskin and Baskin, 2001). For example, the germination of *Amaranthus* species seeds is stimulated by nitrate (Egley, 1986) while that of *I. rugosum* is stimulated by nitric acid and potassium nitrate (Bakar and Nabi, 2003). Pretreatment of seeds by soaking in nitric acid (0.1 N) for 1 day was observed to overcome the low germinability of freshly harvested seeds of *E. glabrescens*, *E. crus-galli*, and *Ludwigia octovalvis* (Kim and Moody, 1989a,b). Calcium-containing fertilizers can also stimulate the germination of certain weed species that are important in rice cropping systems. For example, Lundy et al. (2010) observed that calcium stimulated the germination of *C. difformis*, *Heteranthera rotundifolia*, *Ammannia coccinea*, *Schoenoplectus mucronatus*, *Bacopa* spp., and *Sagittaria montevidensis*. The authors speculated the usefulness of surface applications of calcium phosphate for stimulating weed emergence in stale seedbed management. Despite the theoretical appeal of these fertilizer strategies, few field studies have demonstrated their practicality and results even within a single species have been highly variable in practice (Brainard et al., 2006; Dyer, 1995). In general, field studies have revealed highly variable responses of germination to fertilization due in part to intraspecific variation in germination response (Brainard et al., 2006), variable levels of ambient nutrients, and interactions with other environmental factors including light (Gallagher and Cardina, 1998). Moreover, the economic and environmental costs associated with the application of fertilizers prior to planting may represent a significant constraint to adoption.

2.5.1.3 Optimizing Methods of Killing Weeds in Stale Seedbeds

Multiple methods to kill germinated weeds immediately prior to crop planting have been examined. These typically include light tillage, the use of broad-spectrum herbicides, or flame weeding. In most cases, authors concluded that the use of herbicides and flame weeding are preferable to tillage because they do not stimulate subsequent flushes of weeds and do not bring new weed seeds into the germination zone (Caldwell and Mohler, 2001). For example, Renu et al. (2000) found that the use of a nonselective herbicide in a stale seedbed was more effective than mechanical weeding in reducing weeds in DSR. Likewise, Caldwell and Mohler (2001) found that flame weeding and glyphosate in stale seedbed were more effective than mechanical methods in suppressing the emergence of key weeds in vegetable production systems in New York.

In rice systems in some parts of the United States, where rice is not rotated with other crops during the cool season, stale seedbeds involve field preparation in the fall following rice harvest, with no subsequent tillage occurring in the spring (Harrell et al., 2011; Hill et al., 1994). For example, in DSR production areas in Louisiana, a growing number of producers have shifted to seedbed preparation in the fall, with weeds controlled either through flooding overwinter or through herbicide applications just before rice planting (Harrell et al., 2011). In Brazil, in no-till irrigated rice systems with stale seedbed, a combination of glyphosate and 2,4-D applied 15 days after weedy rice emergence followed by another cycle of stimulation of weedy rice with irrigation and killing with herbicide resulted in a considerable reduction in the weedy rice seedbank compared to without stale seedbed system (Foloni, 1999).

2.5.1.4 Net Effect of Stale Seedbeds in Rice Cropping Systems

In a field study in India, stale seedbed with one irrigation followed by the application of herbicides to kill emerged weeds prior to rice seeding resulted in 44%–68% lower weed density and 60% lower weed biomass compared to the no-stale seedbed control (Kumar et al., 2013). When two irrigations were used, weed density was 77%–85% lower and weed biomass was >85% lower compared to the control (Kumar et al., 2013). Pittelkowa et al. (2012) in the United States found that in no-till DSR, stale seedbed practices significantly reduced watergrass (*Echinochloa* spp.) biomass by 75% in the first 2 years but did not improve watergrass control during the second half of the study. In DSR in California, the stale seedbed method coupled with zero spring tillage was effective at suppressing the smallflower umbrella sedge (*C. difformis*) by 94% and the aquatic ricefield bulrush (*S. mucronatus*) by 91% compared to CT systems (Linquist et al., 2008). However, the authors noted that success with the stale seedbed technique depended on adjusting the level of soil saturation depending on the weed species present and allowing sufficient time for weeds to emerge prior to herbicide application. For example, species such as ducksalad (*Heteranthera limosa*) and redstem/redberry (*Ammannia* spp.) were not well suppressed due to late emergence. In DSR systems in Kerala, India, Sindhu et al. (2010) observed that grasses were the prominent group that germinated immediately after seedbed preparation, followed by broadleaf weeds. They also observed that compared to the usual practice, stale seedbed for 14 days with two shallow hoeings resulted in a reduction of 80% in the population and 40% in the dry weight of weeds, with the highest benefit–cost ratio.

2.5.2 Stimulating Fatal Germination With Crop and Cover Crop Rotations

Rotational crops (including cover crops) often entail the application of practices which stimulate germination (e.g., tillage and irrigation) as well as those that kill emerged seedlings (e.g., cultivation and herbicides). Rotational crops may result in the germination and death of rice weeds in a manner analogous to the stale seedbed approach described earlier.

As with a stale seedbed, the success of rotational crops in reducing the rice weed seedbank depends on an appropriate stimuli being applied at the right time (when seeds are relatively nondormant), as well as on the use of effective postemergence termination methods. Likewise, the efficacy of rotational crops in promoting fatal germination is likely to be the greatest for weeds with limited dormancy and in rotational crops for which weed management is relatively easy and inexpensive. Indeed, if rice weed seeds are stimulated to germinate in rotational crops and are not effectively terminated, they may exacerbate weed problems through reproduction.

In the rice–wheat rotation of India, the inclusion of mungbean during the fallow period between wheat harvest and rice planting resulted in 84% and 40% reduction in the population of *D. aegyptium* in the subsequent rice crop under ZT and CT systems, respectively (Fig. 2). This was because of the greater emergence of this weed species following irrigation during the mungbean cropping, followed by effective termination using nonselective herbicides (in ZT) and shallow tillage (in CT).

In temperate cropping systems, cover crops have been evaluated for their potential to promote the fatal germination of weed seeds. For example,

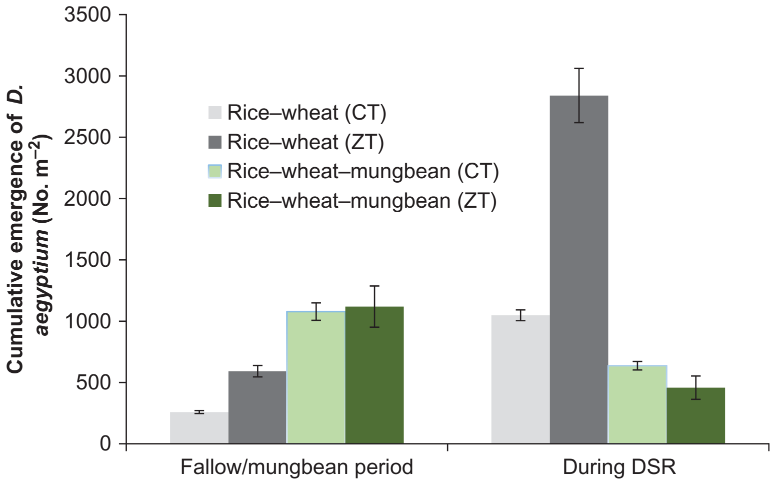

Fig. 2 Effects of crop rotation (by including mungbean) and tillage in the rice–wheat rotation system of India on the cumulative emergence of *Dactyloctenium aegyptium* during fallow/mungbean period and during the subsequent direct-seeded rice crop (Kumar et al., unpublished data).

Mirsky et al. (2010) reported declines in weed seedbanks by encouraging fatal germination associated with soil disturbance in cover crop treatments. Cover crops stimulated weed seed germination and the germinated weeds were either suppressed by the cover crop or controlled by subsequent tillage and preempted weed seed rain. The stimulative effect of certain cover crops has been proven particularly helpful in the management of parasitic weeds. In upland DSR fields in East Africa, green manure (*Crotalaria ochroleuca*, *M. invisa*, and *Cassia obtusifolia*) exhibited a potential to induce the suicidal germination of *S. asiatica* (Kayeke et al., 2007). The cover crops in this case served as a false-host by stimulating the germination of *Striga* without providing conditions necessary for survival.

2.6 Inhibiting Germination and Emergence

2.6.1 Suppressing Emergence Through Propagule Burial

Once dormancy has been broken and the seed has germinated, its ability to reach the soil surface varies considerably by species. Many experiments (Aulakh et al., 2006; Begum et al., 2006; Benvenuti et al., 2004; Chauhan and Johnson, 2010; Lee and Moody, 1988a; Rao and Moody, 1995) have been conducted to estimate the maximum depth of emergence by placing weed seeds at specific depths in the soil. A few experiments have also been conducted to determine weed emergence depth from natural weed seedbanks (Buhler and Mester, 1991). For some species, emergence can only occur from the upper few centimeters. For others like *Eleocharis kuroguwai*, emergence can occur from depths of 15 cm or more (Kim et al., 1996).

In general, emergence decreases with increased depth (Table 5). For example, *F. miliacea* and *C. difformis* exhibited higher emergence from the surface and no emergence from a depth of $\geq$1 cm (Begum et al., 2006; Chauhan and Johnson, 2009d). *L. chinensis* seedlings also failed to emerge from burial depths of >5.0 cm (Benvenuti et al., 2004). The production of established plants and the rate of emergence of aerial shoots of *Cynodon dactylon* were lower for stolon than for rhizome fragments and the differences were enhanced by the effects of depth in the soil (Fernandez, 2003). Few shoots emerged from rhizomes buried below a depth of 10 cm (Phillips and Moaisi, 1993).

The ability of germinated seeds to emerge at a soil depth is often related to seed or propagule size. Larger seeds with greater carbohydrate reserves have increased ability to emerge from greater burial depths compared to those with lower reserves (Baskin and Baskin, 1998). Conversely, small-seeded species such as *Amaranthus* spp. have limited carbohydrate reserves to support emergence following germination, thus, limiting the depth from which these seedlings can emerge (Ghorbani et al., 1999; Santelmann and Evetts, 1971; Thomas et al., 2006). Emergence of deep-buried seeds is generally inversely correlated with seed weight (Benvenuti et al., 2001). Small aerial seeds of *C. benghalensis* germinate mainly from the upper 5 cm, while its larger subterranean seeds may emerge from depths down to 14 cm (Budd et al., 1979). Similarly, the probability of emergence and the successful establishment of the perennial weeds depend in part on the size of the propagules. For example, *C. dactylon* emergence decreases with the depth of the fragment but increases with the weight of the node and internode (Perez et al., 1995). The seed or propagule mass of different weed species is often correlated with potential shoot elongation and, therefore, helps explain the variation in maximal emergence depths between species (Bond et al., 1999). However, the composition of the seed reserves such as their lipid or protein content varies greatly between genus and families (Earle and Jones, 1962; Kuo et al., 1988) and is not always correlated with seed size.

Because emergence of weed propagules generally declines with burial depth, deep burial of propagules through tillage operations can be an effective method of emergence suppression. However, as tillage moves

Table 5 Seed Burial Emergence Range, Burial Depth for Optimum Emergence, and Burial Depth With No Emergence of Important Weeds of Direct-Seeded Rice Systems

Weed Name	Depth of Emergence (Range in cm)	Optimal Depth of Emergence	No Emergence Occurs From a Depth of (cm)	Additional Comments	References
Grasses					
Echinochloa crus-galli	0 to <8	Soil surface	8	Light stimulates its germination. To achieve substantial suppression of seedling emergence by residue mulching, higher amount of rice residue (6 ton/ha) is needed	Sahid and Hossain (1995) and Chauhan and Johnson (2010, 2011)
Echinochloa colona	0–5	Soil surface	6	Light stimulates its germination. Emergence is suppressed drastically by rice residue mulch of 4 ton/ha or greater	Sahid and Hossain (1995) and Chauhan and Johnson (2009g)
Echinochloa glabrescens	0–4	Soil surface			Rao and Moody (1995)
Dactyloctenium aegyptium	0.5–6	Soil surface to 1 cm	>6	Light stimulates its germination. Rice residue mulch suppresses its emergence drastically at 4 ton/ha or beyond	Chauhan (2011) and Burke et al. (2003)

Continued

Table 5 Seed Burial Emergence Range, Burial Depth for Optimum Emergence, and Burial Depth With No Emergence of Important Weeds of Direct-Seeded Rice Systems—cont'd

Weed Name	Depth of Emergence (Range in cm)	Optimal Depth of Emergence	No Emergence Occurs From a Depth of (cm)	Additional Comments	References
Leptochloa chinensis	0–5	0–2 cm in Italian biotypes (Benvenuti et al., 2004) and surface in Philippine biotypes (Chauhan and Johnson, 2008e)	>5 (Italian biotype); 0.5 (Philippines biotype)	Light strongly stimulates germination as there is no germination under darkness in Philippine biotypes and 80% reduction in Italian biotypes. Variability exists among biotypes from different countries. Philippine population did not emerge when seeds were seeded at 0.5 cm or greater depth but Italian population could emerge from 5 cm depth but with huge reduction	Benvenuti et al. (2004) and Chauhan and Johnson (2008a)
Eleusine indica	0 to <8	Soil surface	8	Rice residue mulch suppresses its emergence drastically at 4 ton/ha or more	Chauhan and Johnson (2008e) and Galinato et al. (1999)
Ischaemum rugosum	0–5	Soil surface (Lim et al., 2015), 0–3 cm (Moon et al., 1999)	>2 (Lim et al., 2015), >5 (Moon et al., 1999)	Light is needed for its germination as there is no germination in darkness. Different biotypes from the Philippines differ in their response to burial depth	Rao and Moody (1995), Moon et al. (1999), and Lim et al. (2015)

Rottboellia cochinchinensis	0 to <10	Soil surface	10		Bolfrey-Arku et al. (2011)
Eragrostis tenella	Soil surface	Soil surface	≥0.5	Light is an absolute requirement for germination. Very sensitive to residue mulching with the exponential decline in emergence with increase in rice residue mulch: 50% decline at 0.5 ton/ha and 100% at 4 ton/ha	Chauhan (2013)
Digitaria ciliaris	0 to <8	0–0.2	8	Less sensitive to residue mulch, only 20% and 32% reduction in emergence with 4 and 6 ton/ha residue mulch, respectively, compared to no mulch	Chauhan and Johnson (2008f)
Digitaria longiflora	0 to <2	Soil surface	2	Light is an absolute requirement for germination. About 54% and 78% suppression in emergence by rice residue mulch of 4 and 6 ton/ha, respectively	Chauhan and Johnson (2008f)
Broadleaves					
Eclipta prostrata	0 to <2	0 or 0 to <2	>0 or 2	Chauhan and Johnson did not observe any emergence of Philippine biotypes at burial depth >0 cm	Wu et al. (2003) and Chauhan and Johnson (2008c)

Continued

Table 5 Seed Burial Emergence Range, Burial Depth for Optimum Emergence, and Burial Depth With No Emergence of Important Weeds of Direct-Seeded Rice Systems—cont'd

Weed Name	Depth of Emergence (Range in cm)	Optimal Depth of Emergence	No Emergence Occurs From a Depth of (cm)	Additional Comments	References
Portulaca oleracea	0–1	Soil surface	2	Sensitive to mulching; rice residue mulch of 4–6 ton/ha drastically reduces its emergence	Chauhan and Johnson (2009h)
Trianthema portulacastrum	0–4	0–2	6	Rice residue mulching up to 6 ton/ha did not affect its emergence	Lee et al. (2011)
Alternanthera philoxcroides	0.5–18	0.5–1.0			Shen et al. (2005)
Amaranthus viridis	0–6	0–2	6		Thomas et al. (2006) and Chauhan and Johnson (2009e)
Amaranthus spinosus	0–4	0	4	Seedling emergence was affected by high rates of rice residue	Chauhan and Johnson (2009e)
Sphenoclea zeylanica	0–3	Soil surface	5	No emergence under aerobic condition and very less only in surface seeded saturated condition. Good germination in surface seeded flooded conditions	Moon et al. (1999)
Ludwigia hyssopifolia	0–0.5	Soil surface	1		Chauhan and Johnson (2009c)

Murdania nudiflora	0–4	0–1	6	Variability exists among biotypes. Wilson et al. (2006) found emergence from seed burial up to 4 cm but Ahmed et al. (2015) found no emergence from seeds buried deeper than 2 cm. Residue mulch at 2.5 ton/ha is required to reduce 50% emergence	Wilson et al. (2006) and Ahmed et al. (2015)
Synedrella nodiflora	0 to <2	Soil surface	4	Light stimulates germination. Small proportion of germination in darkness. Response of residue mulch varies with types of seeds (disc or ray floret)—disc type are more sensitive than ray	Chauhan and Johnson (2009f)
Commelina benghalensis	0–5	0.1–0.5	10		Matsuo et al. (2004) and Dias et al. (2009)
Borreria ocymoides	0 to <5	0–0.2	5		Chauhan and Johnson (2008d)
Chromolaena odorata	0 to <2	Soil surface	3	Seedling emergence and seedling dry matter was greatly reduced with the addition of crop residue to the soil surface at rates equivalent to 4–6 ton/ha	Ismail et al. (1996) and Chauhan and Johnson (2008g)

Continued

Table 5 Seed Burial Emergence Range, Burial Depth for Optimum Emergence, and Burial Depth With No Emergence of Important Weeds of Direct-Seeded Rice Systems—cont'd

Weed Name	Depth of Emergence (Range in cm)	Optimal Depth of Emergence	No Emergence Occurs From a Depth of (cm)	Additional Comments	References
Corchorus olitorius	0 to <8	0–2 cm	8	Seedling emergence was reduced by high rates of rice residue (4–6 ton/ha)	Chauhan and Johnson (2008b)
Heliotropium indicum	0 to <2	0–0.2	2	Light stimulates germination	Chauhan and Johnson (2008d)
Melochia concatenata	0 to <8	0–2	8	Seedling emergence was reduced by high rates of rice residue (4–6 ton/ha)	Chauhan and Johnson (2008b)
Mimosa pudica	0 to <8	0–2	8	The rice residue applied to the soil surface at rates of ≤6 ton/ha did not influence the seedling emergence and dry weight	Chauhan and Johnson (2009b)
Tridax procumbens	0 to <3	Soil surface	>3	Seedling emergence and seedling dry matter was greatly reduced with the addition of crop residue to the soil surface at rates equivalent to 4–6 ton/ha	Guimarães et al. (2002) and Chauhan and Johnson (2008g)

Sedges					
Cyperus difformis	0 to <1	Soil surface	≥1	Light is an absolute requirement for its germination. Cold stratification for 2-weeks completely overcomes the light requirement for its germination	Chauhan and Johnson (2009d) and Derakhshan and Gherekhloo (2013)
Cyperus iria	0 to <5	Soil surface	5	Variability exists among biotypes. Philippine biotypes did not emerge when buried in soil at depth ≥ *1* cm (Chauhan and Johnson, 2009d), whereas biotypes from Malaysia could emerge even up to <5 cm (Sahid and Hossain, 1995), no seedlings emerged from seeds buried in soil at depths of ≥1 cm (Chauhan and Johnson, 2009d)	Sahid and Hossain (1995) and Chauhan and Johnson (2009d)
Fimbrystylis miliacea	0 to <1	Soil surface	1	No germination in dark. Light stimulates germination	Begum et al. (2006) and Chauhan and Johnson (2009d)

propagules both up and down in the soil profile (Mohler, 2001; Schonbeck, 2015), this approach will only be effective if propagules are concentrated on the surface prior to tillage. Shen et al. (2005) suggested that deep tillage to invert the soil and bury *Alternanthera philoxcroides* stem fragments up to 20 cm should be effective in controlling emergence, but that subsequent tillage operations may move fragments to less than 10 cm from the surface, resulting in increased emergence. The emergence of key grass and broadleaf weed species in rice declined by 80%–91% under CT with 8-cm tillage depth and by 54%–82% in minimum tillage with 5-cm tillage depth compared to zero-tillage where soil disturbance was limited to rice seeding only (Fig. 3A and B; Chauhan and Johnson, 2009a). The emergence of *R. cochinchinensis*, a grass weed with bigger seed size, was not affected by tillage treatment. A flexible tillage approach, as recommended by Davis (2004), may be more appropriate depending on the situation and weed seed species

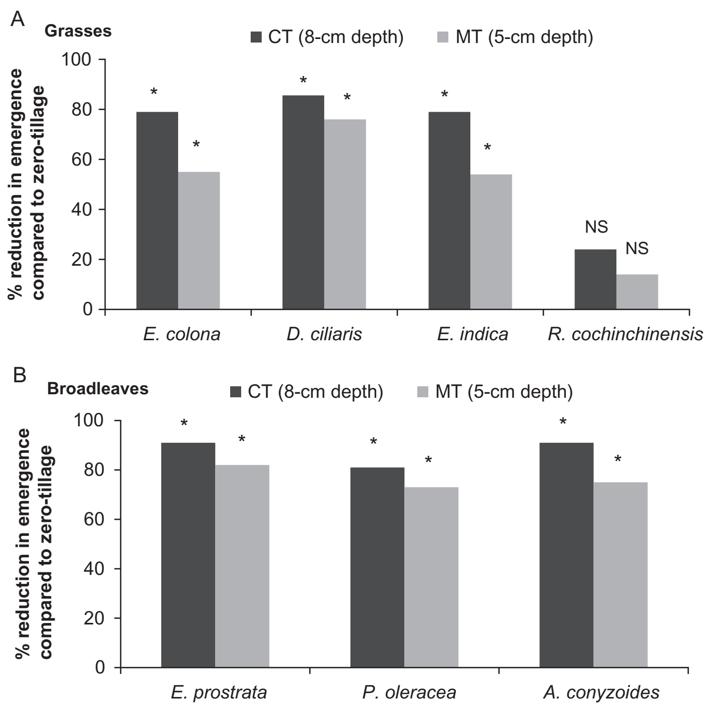

Fig. 3 Reduction in emergence of key grass (A) and broadleaf (B) weed species under conventional tillage and minimum tillage compared to zero-tillage. * indicates significant difference from zero-tillage and NS indicates no difference from zero-tillage. The depth of tillage was 8 and 5 cm for conventional and minimum tillage, respectively. *Modified from: Chauhan, B.S., Johnson, D.E., 2009a. Influence of tillage systems on weed seedling emergence pattern in rainfed rice. Soil Tillage Res. 106, 15–21.*

composition. For example, deep tillage can be an effective approach for weed species with small and short-lived seeds as deep burying will reduce their emergence and the likelihood of loosing seed viability is high by the time seeds again reach the soil surface in the germination zone.

2.6.2 Inhibiting Germination and Emergence With Mulches

Surface mulches may suppress germination or emergence or both, but in most studies only the effects on emergence are observed. Mechanisms by which mulches suppress emergence (postgermination) are likely to be similar to those described earlier for propagule burial. By increasing the distance that shoots must elongate before reaching sunlight, mulches can effectively suppress many small-seeded species since they have insufficient seed reserves to make it to the mulch surface. However, mulches may also inhibit germination through allelopathic effects (Ferreira and Reinhardt, 2010) or changes in edaphic factors including temperature, moisture, and light (Teasdale and Mohler, 1993).

In general, inhibitory effects of residue mulch on weed emergence are greater on small-seeded weeds than on larger-seeded weeds (Liebman et al., 2001). As the majority of the key problematic weeds of rice, however, are small-seeded and sensitive to light and burial depth, residue mulching offers a great opportunity for weed suppression in DSR.

In a series of pot experiments, Chauhan (2012b) evaluated the effect of rice residue mulch levels (0–6 ton/ha) on the seedling emergence of key rice weed species and observed that response was species specific. Some small-seeded species such as *E. colona*, *D. aegyptium*, and *E. indica* were suppressed by as little as 1–2 ton/ha of residue, whereas other weed species required 4–6 ton/ha of residues for significant suppression. A residue load of 4–6 ton/ha significantly suppressed the emergence of dominant rice weed species including *E. crus-galli*, *E. colona*, *D. aegyptium*, *I. rugosum*, *E. indica*, *E. prostrate*, and *M. nudiflora*. Some species such as *T. portulacastrum*, *A. viridis*, and *Ipomoea tribola* were less affected by even higher residue mulch (Chauhan, 2012b; Chauhan and Abugho, 2013; Lee et al., 2011). These results suggest that weed response to residue mulch is complex and depends on various factors including residue load and type, allelopathic effects of residues, weed species, and environmental factors.

In zero-till systems, residue mulching can be a very effective strategy of weed control in DSR where tillage or mechanical weeding is not used for weed control. In a field trial conducted at IRRI, rice residue mulch of 6 ton/ha under zero-till DSR reduced the emergence of major weeds of DSR including *A. spinosus*, *E. prostrata*, *E. colona*, *D. ciliaris*, and *E. indica* by more than 60% compared to without mulching (Chauhan and Abugho, 2013). However, *I. tribola*, a broadleaf weed with bigger seed size, was not affected by 6 ton/ha residue mulch. Similarly, another field study conducted in the rice–wheat cropping system of India demonstrated that retention of wheat residue (5 ton/ha) on the soil surface in zero-till DSR resulted in suppression in the emergence of grass by 73%–76%, broadleaf by 65%–67%, and sedge species by 22%–70% compared to no residue. In both studies, reduction in emergence reduced weed biomass by 54%–96% and 70% in the Philippine and Indian studies, respectively. The use of mulches from other rotational crops including mungbean [*Vigna radiata* (L.) R. Wilczek] or living mulches (e.g., sesbania coculture) may also be effective in ZT rice systems (Kumar et al., 2013).

In the rice–barley rotation of Korea, *E. kuroguwai* was more prevalent with no or little mulch than at higher barley straw mulch rates in the rice crop (Choi et al., 1999). In Jiangxi, China, long-term straw return and organic fertilizer application were found to effectively control weed communities in the paddy field during fallow (Li et al., 2009).

Inclusion of cover crops during fallow periods has a potential to suppress weeds in DSR in several ways. First, cover crops can suppress the growth of weeds and prevent their seed production during the cover crop growth period. After termination, cover crops can suppress the emergence and growth of weeds through residue-mediated effects involving multiple mechanisms including allelopathy (Kumar et al., 2008, 2009a; Weston, 1996), immobilizing N (Dyck and Liebman, 1994; Kumar et al., 2008), mulch effects (Teasdale and Mohler, 1993, 2000), or through interactions with pathogens (Conklin et al., 2002). Cover crops such as buckwheat (Iqbal et al., 2003; Kumar et al., 2008, 2009a,b; Xuan and Tsuzuki, 2004), mustards (Al-Khatib et al., 1997; Haramoto and Gallandt, 2004), rye (Barnes and Putnam, 1983; Yenish et al., 1996), sorghum (Weston, 1996), and legumes such as cowpea, mungbean, and hairy vetch (Hill et al., 2006; Ngouajio and Mennan, 2005) have been reported effective in suppressing weed emergence and growth and are also known for their allelopathic effects.

2.6.3 Inhibiting Germination, Emergence and Growth Through Water Management Using Anaerobic Germination (AG) Tolerant Rice Cultivars

Flooding can reduce both the emergence and growth of the majority of rice weeds (Table 6). Therefore, water management forms the basis for successful weed management in transplanted rice production. Early flooding of ≥5 cm

Table 6 Effect of Flooding Depth, Time, and Duration on Emergence and Growth of Major Rice Weed Species

Weed Name	Flooding Effect on Emergence and Growth	References
Grasses		
Echinochloa crus-galli	Early shallow flooding (0.5–2 cm) at 0 days after sowing (DAS) did not affect emergence but shoot length was reduced but had no effect when flooding was delayed by 4 DAS. Deep flooding of 10 cm at 0 DAS also did not affect emergence, however, its root (∼99%) and shoot lengths (80%) were highly suppressed (Estioko et al., 2014)	Estioko et al. (2014)
	In contrast, other studies observed reduction in emergence at 4-cm flooding depth. Variations in results suggest differential response of biotypes adapted to different environments and management strategies	Chauhan and Johnson (2011)
Echinochloa colona	More sensitive to shallow flooding of 0.5 to 2 cm than *E. crus-galli*. Early shallow flooding of 0.5–2 cm did not affect the shoot length when flooding was delayed by 4 DAS. But root and shoot lengths were suppressed when flooding was initiated at 0 and 2 DAS. Deep early flooding of 10 cm at 0 DAS reduced emergence by 97% compared to no flooding control	Estioko et al. (2014)
Echinochloa glabrescens	Flooding is more effective in suppressing growth than emergence. If flooding is delayed by 4 DAS, there is no effect on emergence but growth is suppressed. When flooding is delayed by 8 DAS, there is no effect on either emergence or growth even with increase in flooding depth. For 50% reduction in growth, shallow flooding of 2 cm should be introduced within the first 2 days and if flooding is delayed by 4 DAS, then a flooding depth of 4 cm is needed for 50% biomass reduction. Half the recommended rate of pretilachlor with safener when combined with early shallow flooding of 2 cm suppressed emergence by 95% compared to nontreated flooded treatment	Opena et al. (2014)
Dactyloctenium aegyptium	Flooding of 2.5 cm water completely inhibits germination and emergence	Kumar et al. (2013)

Continued

Table 6 Effect of Flooding Depth, Time, and Duration on Emergence and Growth of Major Rice Weed Species—cont'd

Weed Name	Flooding Effect on Emergence and Growth	References
Leptochloa chinensis	Philippine population: At a 2 cm flooding depth, emergence is reduced by 26% when flooded 2 out of 7 days but suppression further increased to 73% when field is kept continuously flooded for 7 days. A 10 cm flooding resulted in 90%–99% reduction in emergence. Flooding had a more pronounced effect on growth than emergence. A flooding of 2 cm resulted in 99% reduction in biomass when continuously flooded for 7 days and 73% when flooded 2 out of 7 days	Chauhan and Johnson (2008a)
	Northern Italy population: A 2 cm flooding depth did not affect emergence. Flooding depths of 4 and 6 cm resulted in 35% and 85% reduction in emergence, respectively. No emergence was recorded above water level when flooding depth was 8 cm	Benvenuti et al. (2004)
Ischaemum rugosum	Continuous flooding of 2, 4, and 6 cm depths for 21-days reduced seedling emergence by 88%, 94%, and 95%, respectively. With delay in flooding, emergence is reduced by 29%, 35%, and 36% when delayed by 2 DAS, by 24%, 26%, and 30% when flooding is delayed by 4 DAS, and by 24%, 25%, and 27% when flooding is further delayed by 8 DAS, respectively, at 2, 4, and 6 cm flooding depths. No effect on growth when flooding is delayed by 8 DAS. However, flooding on the same day of seeding reduced biomass by 80%, 96%, and 98% at 2, 4, and 6 cm flooding depths, respectively	Lim et al. (2015)
Broadleaved		
Eclipta prostrata	Growth is reduced with deep flooding (10 cm) at or before four-leaf stage	Kumar et al. (2013)
Ludwigia hyssopifolia	Shallow flooding of 2 cm for 4 days out of 7 days reduced emergence by 71% and biomass by 97%. Flooding of 10 cm when delayed by 21 DAS did not affect the growth of this weed species	Chauhan and Johnson (2009c)
Ludwigia octovalvis	No emergence was observed at 3 cm flooding depth regardless of seed burial depth	Moon et al. (1999)

Table 6 Effect of Flooding Depth, Time, and Duration on Emergence and Growth of Major Rice Weed Species—cont'd

Weed Name	Flooding Effect on Emergence and Growth	References
Sphenoclea zeylanica	Emergence increased under flooded condition. No emergence under aerobic conditions	Moon et al. (1999)
Murdania nudiflora	Flooding had a more pronounced effect on seedling biomass than seedling emergence. Surface seeded seed emergence was less affected by flooding than buried seeds. For example, emergence reduction was 7%, 9%, and 19% when seeds were at surface, whereas reduction increased to 63%, 100%, and 100% when seeds were buried at 0.5 cm depth at 2, 4, and 6 cm flooding depths, respectively. Biomass was reduced by 78%, 92%, and 96% at flooding depths of 2, 4, and 6 cm, respectively, for the seeds placed on the soil surface, whereas for the seeds buried at 0.5 cm, these values were 78%, 100%, and 100%	Ahmed et al. (2015)
Sedges		
Cyperus difformis	Shallow (2 cm) 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 stages (21 DAS)	Chauhan and Johnson (2009d)
Cyperus iria	Shallow (2 cm) intermittent flooding reduced emergence by 45%, which increased to 94% with continuous flooding. Continuous flooding of >2 cm completely inhibited emergence and growth. Flooding at 7 DAS reduced growth by 94%, but was less effective at later stages (21 DAS)	Chauhan and Johnson (2009d)
Fimbrystylis miliacea	More sensitive to flooding than *C. difformis* and *C. iria*. Intermittent flooding (4 out of 7 days) at shallow depth (2 cm) reduced emergence by 94%, which increased to 100% inhibition with continuous flooding of 2 cm or more	Chauhan and Johnson (2009d, 2010)

depth has been found effective in managing many dominant grass (*E. colona*, *E. crus-galli*, *L. chinensis*, *D. aegyptium*, etc.) and sedge (*C. iria*, *C. difformis*, *F. miliacea*) weed species but some of the broadleaf weed species are adapted to early flooding including *Monochoria vaginalis* and *S. zeylanica* which can germinate and emerge even from deeper flooding depth (Kent and Johnson, 2001; Pons, 1982). Weed emergence and growth are highly influenced by flooding timing, duration, and depth (Table 6). Maximum benefit of flooding on the suppression of weed emergence and growth is achieved when flooding is established at an early stage—immediately after crop establishment. In DSR systems, opportunities to reduce weed emergence through flooding are limited, since early flooding to suppress weeds will also suppress rice emergence as current rice cultivars do not tolerate anaerobic conditions at germination/emergence phase. In DSR, flooding is only possible after crop emergence when most weeds already emerged and flooding is less effective on emerged weeds (Table 6). Rice cultivars which can tolerate anaerobic condition/flooding at germination phase are referred to as "anaerobic germination (AG) tolerant rice" which can facilitate the advantage of early flooding for weed control in DSR systems. Work on the development of AG-tolerant rice is underway at IRRI. After screening a large number of gene bank accessions and breeding lines (>8000), IRRI has identified several landraces with the AG-tolerance trait including Khao Hlan On from Myanmar, Ma Zhan Red from China, Khaiyan, Kalongehi, and Dholamon-64-3 from Bangladesh, and Nanhi from India (Angaji et al., 2010). Promising quantitative trait loci (QTLs) have been identified through analysis of mapping populations derived from these tolerant genotypes. Major QTLs for AG tolerance derived from Khao Hlan On and Ma Zhan Red have been identified. Given the likelihood of advances in tolerant rice varieties, therefore, knowledge of the impact of flooding duration, timing, and depth may suggest best-bet strategies to manage weeds in DSR using AG-tolerant cultivars or cultivars with early and faster growth which enable early flooding in DSR.

Understanding the effects of time, duration, and depth of flooding under different soil and crop establishment method, is critical for managing weeds effectively using precise and efficient use of irrigation water. This information would be useful in suppressing weeds after herbicide application or hand/mechanical weeding under DSR without AG-tolerant rice and using precise flooding at an early stage with AG-tolerant cultivars. Moreover, most of the information on the response of weed species to flooding is generated under transplanted rice or wet-DSR conditions in which soil is puddled.

According to Smith and Fox (1973), weed emergence and growth suppression to flooding is dependent on the physical, chemical, and biological properties of submerged soil which is highly influenced by the type of tillage (wet, dry, or zero-tillage).

3. INTEGRATING AND PRIORITIZING PREVENTIVE STRATEGIES

No single preventive strategy will be sufficient to suppress weeds in DSR, and some individual tactics may be counter productive or prohibitively expensive depending on the cropping system and weed community. Key preventive strategies and tactics are summarized in Table 7, along with the weed and cropping system characteristics for which they are likely to be most effective. The important potential tradeoffs and costs associated with each tactic are also presented.

Some preventive tactics may suppress weeds at more than one critical life stage and may, therefore, be of particular practical importance in a wide range of cropping systems. For example, planting well-adapted smother crops on bunds may simultaneously (i) prevent reproduction of important rice weeds while (ii) providing beneficial habitat for seed predators that promote seed predation. On the other hand, some tactics may have contradictory impacts on different weed life stages and may possibly result in an increase in net costs. For example, delaying tillage following rice harvest may (i) promote seedbank decline by leaving seeds on the soil surface where they are most vulnerable to predators and decay agents, but may also (ii) allow established perennials to grow and reproduce free from mechanical disturbance.

Weed management tactics must also be compatible with overall crop management goals if they are to be adopted by growers. Of primary importance in this regard are the costs relative to their expected benefit. For example, long-distance dispersal of weed seeds by ducks may be a mechanism by which certain weeds colonize fields, but preventing such introduction may be expensive or impossible and may have negligible impact on key weeds of rice. Other more plausible tactics such as stale seedbeds using presowing irrigations may entail costs (e.g., pumping; herbicides) that outweigh savings associated with improvements in weed management during rice production. Moreover, practices designed to suppress weeds may have detrimental impacts on other aspects of the farming system that result in unacceptable economic or environmental costs. For example, retention of crop residue

Table 7 Summary of Preventive Weed Management Strategies and Tactics

Strategy	Tactic	Timing	Characteristics of Target Weeds	Characteristics of Target Cropping System	Additional Benefits	Constraints/Costs
Prevent seed and propagule production	Remove reproductive weeds from bunds	Whenever rice weeds are producing seeds (close to rice harvest)	Reproduce on bunds; wind or water dispersed	Small field size; steep slopes (high bund:field ratio)		Treatment costs; bund-weeds may promote beneficial, reduce erosion
	Plant smother crops on bunds	During and/or after rice production	Reproduce on bunds; wind or water dispersed	Small field size; steep slopes (high bund:field ratio)	Habitat for beneficial; erosion protection; fodder or cash crop value	Seed and management costs; habitat for pests
	Spray or plow down reproductive weeds following rice harvest	After rice harvest/ during fallows	Vigorously grow and produce significant seeds after rice harvest or during fallow period	Fallow after rice		Herbicide or labor costs; weeds may have value as fodder or reduce erosion
Prevent dispersal	Use certified weed-free seeds; sieve rice seeds	At the time of rice seeding	Matures with rice; same size as rice	DSR	Seed quality	Seed and sieving cost

	Filter irrigation intake	During time that rice weeds produce seeds (e.g., for subsequent crop)	Floating seed; sheds seed at time of irrigation	Irrigated; lowland		Filter cost
	Avoid contaminated compost and manure	At the time compost and manure applied	Palatable to livestock; survives ingestion and composting			Treatment costs; soil health costs if nothing applied
	Clean planting and harvesting equipment	At planting and harvest time	Adhering to seeding/harvesting machinery; species which synchronize maturity with crop	Mechanized production systems; service providers	Limit dispersal of disease propagules; minimizes seed contamination	Cost of cleaning; delayed planting or harvesting
Promote predation	Establish plant habitats on bunds or field borders that are attractive to predators	During cropping and fallow period	Palatable to predators	Small field size; steep slopes (high bund:field ratio)	Erosion protection; fodder or crop value; habitat for pest predators	Seed and management costs; habitat for pests
	Avoid broad-spectrum insecticides	During fallow and cropping period	Palatable to insects		Preserve other beneficial (e.g., insect predators)	Potential insect pest outbreaks
	Delay or eliminate tillage to retain seeds on soil surface and avoid predator disruption	After weed seed shed (after rice harvest)	Palatable to predators; shed seed at time of rice harvest	Fallow after rice; zero-till compatible crop after rice (e.g., wheat; lentils)	Residue retention for subsequent crop; lower tillage costs	Existing weeds may produce seeds or propagules unless herbicides are applied

Continued

Table 7 Summary of Preventive Weed Management Strategies and Tactics—cont'd

Strategy	Tactic	Timing	Characteristics of Target Weeds	Characteristics of Target Cropping System	Additional Benefits	Constraints/Costs
Promote decay	Delay or eliminate tillage to retain seeds on surface and potentially promote decay agents	After weed seed shed (after rice harvest)	Susceptible to decay agents; shed seed at time of rice harvest	Fallow after rice; zero-till compatible crop after rice	Residue retention for subsequent crop; lower tillage costs	Existing weeds may produce seeds or propagules unless herbicides are applied
	Flood	After weed seed shed (after rice harvest)	Decay promoted by submergence	Irrigation available; low soil permeability; fallow after rice		Cost of irrigation; may kill seed predators
Promote fatal germination	Stale seedbed via preirrigation followed by herbicides, shallow tillage or flooding	Weeks to months before rice planting	Nondormant at time of irrigation; seeds with physical dormancy and no photoblastism	Irrigated; fallow preceding rice planting; zero-till rice		Irrigation cost; herbicide or tillage cost
	Stale seedbed via shallow tillage followed by herbicides, a second shallow tillage or flooding	Weeks to months before rice planting	Nondormant at time of first tillage; germination stimulated by tillage (e.g., light sensitive)	At least 2 weeks fallow preceding rice planting; zero-till rice		Tillage and/or herbicide cost; soil erosion
	Rotation with crops in which irrigation and/or tillage are used	Months before rice planting	Nondormant at time of tillage or irrigation		Fodder or cash crop value	Crop production costs; risk of weed escapes and seed production

Prevent emergence	Inversion tillage to bury propagules below germination zone	Last tillage event before rice planting	Small seeds	Conventional tillage; propagules concentrated in surface layers	Simultaneous incorporation of manures	Soil degradation; tillage costs; only effective if most seeds are in surface layers; may stimulate new flush of weeds
	Mulching with crop or cover crop residue	Before and during rice planting	Small seeds; seeds susceptible to allelopathy	Zero-tillage	Soil improvement; moisture retention	May interfere with rice establishment; requires specialized planting equipment
	Flooding	After rice establishment, or at planting in combination with submergence-tolerant rice	Small seeds; aerobic species	Submergence-tolerant or rapid emerging rice		Will only work for weeds with delayed emergence relative to rice or with submergence-tolerant rice
	Incorporate suppressive cover crop or crop residue	Days to weeks before rice planting	Seeds susceptible to allelopathy, or fungal attack; seeds responsive to nitrogen availability	Conventional tillage with sufficient fallow period to grow suppressive cover crop or crop residue	Soil improvement	Seed and management costs; forgone livestock fodder value

to suppress weed emergence may be detrimental to crop establishment or may divert residue from more productive alternative uses (livestock feed), resulting in net economic losses.

Given our current state of knowledge of both the biological and economic impact associated with different preventive strategies, it is challenging to make specific recommendations. Nonetheless, a critical examination of studies associated with specific tactics suggests a number of approaches that warrant further study given their potential to prevent weed infestations at relatively low costs, while providing other economic benefits and ecosystem services.

3.1 Integrating Stale Seedbeds and Crop Rotations During Fallows

As discussed in detail in Section 2.5.1, the stale seedbed technique involves stimulating weed germination prior to crop planting or emergence, and subsequently killing weeds in order to reduce the seedbank before rice. In zero-till DSR, this may be achieved through irrigation to stimulate flushes of weeds, followed by applications of herbicides such as glyphosate to kill weeds prior to planting rice. Adoption of this technique coupled with zero or minimal soil disturbance prior to seeding rice can dramatically reduce weed control requirements during rice growth due to the depletion of weed populations from the upper soil layer and to the diminished weed emergence with the crop (Fischer et al., 2009). This method is used in Asia (Lal et al., 2004), Europe (da Silva and Fátima, 2001), mid-southern (Bond et al., 2005), and southern (Watkins et al., 2004) United States, and South America (Salazar et al., 2002). In South America and Europe, stale seed bed is used for the control of red rice (Ferrero, 2003; Fischer and Antigua, 1997). Pittelkowa et al. (2012) has suggested no-till stale seedbed practices as a component of integrated weed management strategies in direct water-seeded rice as it resulted in the significantly improved management of sedge and grass weeds. The rice yield equivalent to that of a weed-free crop environment was reported with DSR under the stale seedbed system (John and Mathew, 2001).

In areas where dry season fallows are the norm, inclusion of a weed-suppressive cash crop or cover crop prior to rice can have beneficial effects for weed suppression similar to those described for stale seedbeds. Production of crops or cover crops during fallow periods requires irrigation which stimulates weed emergence. If weeds in rotational crops are effectively controlled and prevented from producing seeds, the result is a reduction in the seedbank prior to rice planting. Fallow period crops and cover crops can also provide weed-suppressive mulches for subsequent no-till planting of rice (Becker and Johnson, 1998; WARDA, 1999). In addition to weed suppression, rotational cash or cover crops may provide multiple benefits including improvements in soil health, recycling of nutrients, protection of soil from water and wind erosion, reduction in nutrient leaching and erosion, and addition of N to the soil (in the case of legume species) (Barberi, 2002; Martini et al., 2004), as well as a source of income.

For example, inclusion of mungbean in the fallow period (after the harvest of wheat and planting of following rice crop) in the rice–wheat system in India reduced the emergence of *D. aegyptium* during the rice phase by 40% and 84% in CT and ZT systems, respectively compared to a standard bare fallow (Fig. 2). Similarly, some legume crops (Lecuna and Stylo) in the fallow period reduced the weeds in the subsequent rice crop grown after legume or fallow period in Africa (WARDA, 1999). *Stylosanthes guianensis* (Stylo) is one of the most promising forage legume species for soil fertility improvement and weed suppression in the savanna agroecosystem of West Africa (Becker and Johnson, 1998). Stylo fallow can increase rice yields compared a natural fallow (Becker and Johnson, 1998; Saito et al., 2006) and can reduce weed biomass as shown in northern Laos (Roder et al., 1998; Saito et al., 2006). Manual tillage combined with Stylo fallow are recommended to small-holder farmers to improve upland dry-seeded rice productivity (Saito et al., 2010).

3.2 Reduced Tillage With Residue Retention

In some situations, reduced tillage combined with residue retention may be an effective approach to managing weeds through prevention. In theory, reductions in tillage can suppress weeds through a variety of mechanisms including: (i) retention of seeds on the soil surface where they are most vulnerable to predators and decay agents; (ii) improvement in habitat for soil dwelling seed predators; (iii) promotion of soil-borne agents of seed and propagule decay; (iv) reduction of tillage-induced stimulants of seed germination including light, oxygen, and nitrogen; and (v) retention of weed-suppressive surface-mulches from the previous crop. On the other hand, reductions in tillage may facilitate the establishment of perennial weed species or increase the emergence of weeds as majority of weeds are in the germination zone. It may also result in a shift toward weed communities that are well adapted to low soil disturbance.

The net effect of reduced tillage on weed seedbank density in rice cropping systems has been examined in several studies (Govindan and Chinnusamy, 2014; Lal et al., 2016; Mishra and Singh, 2012) and discussed in several recent reviews (Chauhan and Johnson, 2010; Erenstein and Laxmi, 2008). These studies generally showed that under reduced tillage, the proportion of perennial weeds, as well as grasses and sedges, often increases over time. For example, Mineta et al. (1997) found that the population of perennial weeds *Rumex crispus* subsp. Japonicas and *Ranunculus cantoniensis* subsp. Cantoniensis, and wind-dispersing weed species such as *Conyza sumatrensis*, *Erigeron canadensis*, *C. canadensis*, *Lactuca indica* var. Laciniata, and *S. oleraceus* increased in fields where mulching and ZT cultivation were applied. Similarly, in DSR systems, continuous zero-tillage increased the population density of *E. colona* and *C. iria* while rotational tillage systems significantly reduced the seed density of *C. iria* and *Medicago hispida* compared to continuous ZT or CT systems (Mishra and Singh, 2011).

Although increases in certain weed species can occur in ZT, the integration of mulch residues with ZT can reduce weed populations relative to CT. Mulches tend to suppress weed emergence and reproduction (see Section 2.6.2) under ZT, and over time the density of seeds in the germination zone can be gradually depleted as new seeds are not brought back to the surface via tillage. In Santa Maria, Rio Grande do Sul of Brazil, for example, reduced red rice seedbank density was observed under ZT (597 seeds m^{-2}) compared to CT (1994 seeds m^{-2}) in ZT water-seeded rice (Avila et al., 2000). Similarly, in Costa Rica, ZT-DSR into stubble resulted in a progressive decrease in the seedbank density of red rice compared to conventional till DSR (Ortega and Agüero, 2005). In the northern part of India, Singh et al. (2007) concluded that retention of wheat residue mulch at 4 ton/ha and Sesbania intercropping for 30 days were equally effective in controlling weeds associated with dry-DSR.

Reduced tillage and residue retention are not only potentially helpful in suppressing weeds but also represent critical components of conservation agriculture with multiple potential benefits for rice cropping systems (Hobbs et al., 2008; Kumar and Goh, 2000). Under reduced tillage systems with residue retention, improvements in water retention, temperature buffering, and soil health are well known. Although mulches have great potential for suppressing weeds in DSR and improving the sustainability of rice cropping systems, the practicality of mulch retention depends on tradeoffs between competing uses for crop residues such as for livestock feed (Baudron et al., 2015) as well as the availability and reliability of specialized equipment for the successful establishment of rice in the presence of residue (Singh and Sidhu, 2014). Further research is needed to understand these tradeoffs and to identify strategies to reduce the costs associated with mulch retention before mulching will be widely adopted.

3.3 Rotational Tillage and Establishment Methods

Rotational tillage systems—which involve occasional use of tillage in rice or rotational crops—have several potential advantages for preventing weed problems in DSR (Hill, 1998). Within DSR, these tillage systems have several practical benefits relative to ZT such as improved crop production (Hill, 1998), increased short-term N use efficiency, accelerated rates of residue decomposition and microbial-N mineralization, (Doran, 1987), and reduced populations of troublesome weed species (Peachey et al., 2006). Significant reduction in the soil seedbank density of rice flat sedge (*C. iria* L.) in direct-sown rice, and wild oats [*Avena ludoviciana* (L.) Dur.], and toothed burclover (*M. hispida* Gaertn.) in wheat was observed with rotational tillage systems [that alternated between CT and ZT (ZT–CT and CT–ZT)], compared to continuous zero-tillage (ZT–ZT) or CT (CT–CT), in rice–wheat cropping system (Mishra and Singh., 2012). Since reduced tillage favors some species and CT favors others, it has been suggested that varying tillage systems will bring about maximum benefits for weed management (Mishra and Singh, 2012; Peachey et al., 2006).

Rotating crop establishment methods, i.e., DSR with traditional transplanting systems or dry-DSR with wet- or water-seeded DSR may facilitate improved weed management. As noted earlier, while DSR has important advantages in terms of labor savings, it often exacerbates weed problem relative to transplanting since the size differential between weeds and crops is lost and since early flooding cannot be easily used (Rao et al., 2007). By rotating DSR with transplanting, the buildup of problematic weeds may be delayed or eliminated. For example, inclusion of flooded-transplanted rice in the rotation is likely to reduce aerobic weed species sensitive to flooding such as *E. colona*, *F. miliacea*, *L. chinensis*, and *D. aegyptium* (Kim and Moody, 1989a,b; Mortimer et al., 2005). Conversely, inclusion of DSR may help suppress aquatic weed species that dominate PTR (Rao et al., 2015). Hence, alternating DSR and PTR may improve weed suppression and reduce pressure of difficult-to-control weeds in both systems. Pittelkowa et al. (2012) demonstrated that rotation of tillage and crop establishment systems can lead to improved weed control in DSR. Rice established by different methods uses different water and other management methods which in turn influence the associated weed species. For instance, weed species favoring aerobic soil conditions are suppressed in the water-seeded method of rice establishment (Hill et al., 1994) while the dry-seeded method of rice establishment suppresses weeds that are adapted to anaerobic conditions (Mortimer et al., 2005). Similarly, through the adoption of rotational tillage, weeds that need light for germination may be suppressed when left in deeper soil layers after deeper tillage or when retained on top layers in the germination zone for their seeds to be exhausted by adopting zero-tillage.

Although rotational tillage and crop establishment may be helpful in suppressing weeds in DSR, this approach has several limitations. First, it is likely to be beneficial only for weed species with limited persistence. For weed species with highly persistent seeds, seeds can readily survive tillage and flooding events and may increase in abundance as tillage brings new seeds to the soil surface. Finally, these rotational approaches entail costs for growers who need to maintain two different equipments for the distinct tillage, flooding, and establishment methods required of the different systems.

3.4 AG-Tolerant Rice and Flooding

Flooding at early stages has been one of the most important components of weed control in PTR, where flooding is established on the day of transplanting. The maximum suppressive effects of flooding on weed emergence and growth are obtained when fields are flooded immediately after sowing (Table 6). So far, the advantages of early flooding in DSR systems for weed control have been limited because rice establishment is also adversely affected if flooding is established immediately after rice seeding. However, with the advancement in the development of AG-tolerant cultivars (see Section 2.6.3), the advantage of early flooding for weed control would also be possible in DSR systems. In California, USA, farmers shifted from dry seeding to water seeding to take advantage of early flooding to manage difficult-to-control weeds such as *Echinochloa* species and weedy rice (Hill et al., 2001). Once these AG-tolerant cultivars are available to farmers, early flooding can be exploited in DSR systems for weed control in regions where water is not limited.

The integration of AG-tolerant cultivars and early flooding shows promise for weed management in DSR, but optimization of this approach, especially under water-limited environments, will require further study. Nevertheless, rice cultivars with AG-tolerance traits would help make the DSR system more successful both in irrigated and rainfed areas in terms of weed control and in improving crop establishment which otherwise is being adversely affected if untimely rain comes soon after seeding, leading to flooding.

3.5 Integrated Bund Management

Bunds occupy a significant portion of the arable rice production area in many parts of the world. Bunds play a critical role in retaining moisture/water on sloped ground, providing access to fields, and delineating ownership. Bunds may, however, serve as sources of weed propagules if poorly managed. On the other hand, well-managed bunds may provide a source of income through the production of cash crops, and may become a beneficial habitat for predators of rice pests, including weeds. In combination with changes in irrigation timing and frequency, bund management may enhance beneficial insect populations and promote seed predation.

The overall impact of weeds on rice bunds is difficult to quantify, but very likely negative compared to when bunds are covered with planned weed-suppressive vegetation. As noted in Section 2.1.1, weeds on bunds can be a substantial source of weed seeds in rice fields. They may also serve as alternate hosts for insect or disease pests of rice, maintaining their populations during the off-season. For example, a survey in Sri Lanka revealed that weeds on bunds helped maintain populations of rice bug (*Leptocorisa oratorius*) and their elimination from bunds was recommended for insect pest management (Rajapakse and Kulasekera, 1980). On the other hand, in the "Kekulam" method of paddy cultivation used in Sri Lanka, it is recommended that weeds be maintained on bunds to promote beneficial insects including predators of paddy insect pests, and predators of weed seeds including ants (Upawansa, 1999). Similarly, in Indonesian rice fields, maintenance of strips of weed species including *M. vaginalis*, *F. miliacea*, *C. iria*, and *Limnocharis flava* resulted in greater abundance of predatory insects of rice pests (Karindah et al., 2011).

Optimal weed management on bunds will likely require a balanced approach whereby plant species that are major weeds in rice (or rotational crops) and those that serve as alternate hosts of disease or insect pests are suppressed, and those that have known benefits for hosting beneficial insects are tolerated or even promoted. Although rice weeds may promote beneficial insects (Karindah et al., 2011), these benefits must be weighed against the costs associated with seed production and dispersal into adjacent rice fields. Identification of wild plant species with known benefits, as well as cultivated plants or cover crops with multiple desirable properties, will be helpful in designing bund plantings that are both ecologically beneficial and economical.

Way and Heong (1994, 2009) have pointed to bunds as a critical habitat for beneficial insects and suggested that manipulations in bund habitat, along with changes in the timing and frequency of irrigation, could enhance the ecosystem services provided by these insects. Since fire ants and spiders are often very abundant on bunds, and move back and forth between bunds and rice fields to avoid flooding and obtain food, Way and Heong (2009) recommend periodic drainage to promote these beneficial for insect pest management. Since fire ants are well-known predators of weed seeds, feeding preferentially on grass species (Risch and Carroll, 1986), this approach may have value for the enhancement of the seed predation of weeds known to be particularly problematic in DSR.

Alternative bund management systems are most likely to be adopted if they have both ecological and economic benefits. Unfortunately, only a few studies have examined the full impacts of alternative bund management practices on rice cropping systems. For example, Tengco et al. (1988) found that growing grasses such as *Setaria anceps*, *S. splendida*, and *B. ruziziensis* on bunds in the Philippines resulted in a substantial quantity of herbage production while controlling other weeds. The study, however, did not examine the impact of these grasses on insect pests. Likewise, entomological studies have pointed to benefits of weedy vegetation in the promotion of beneficial insects (Karindah et al., 2011; Way and Heong, 2009), but rarely discussed tradeoffs associated with weed seed production and dispersal, nor the economic costs associated with changes in bund vegetation management or irrigation scheduling. Clearly, interdisciplinary studies are needed to fully optimize bund management systems.

4. FUTURE RESEARCH PRIORITIES

This review has revealed multiple gaps in knowledge that would be helpful in optimizing weed management in DSR through the integration of preventive approaches. Among the key priority research areas identified were:

- **i.** Quantifying the effects of fallow management (with and without cover or rotational crops) on weed seed production, on the weed seedbank and the economic implications at cropping system level.
- **ii.** Evaluating the effects of crop rotation on weedy population dynamics.
- **iii.** Evaluating the rotation of tillage and establishment methods on weed management in DSR systems, especially for the management of difficult-to-control weeds of DSR.
- **iv.** Optimizing stale seedbeds through improved understanding of emergence periodicity of major weeds of DSR; factors which stimulate weed seed germination (e.g., timing of dormancy release, response to irrigation and tillage); and timing and method of killing emerged weeds.
- **v.** Quantifying the role of irrigation water and manure/compost in weed seed dispersal and developing strategies to minimize it.
- **vi.** Assessing the effect of tillage, soil amendments (including crop residue and compost), and water management on weed seed persistence in DSR-based systems.
- **vii.** Interdisciplinary studies on optimizing bund management using proper vegetation and irrigation scheduling on weed, insect pest, and disease suppression by studying its impact on weed seed predators and beneficial insects.
- **viii.** Optimizing the time, duration, and depth of flooding for AG-tolerant rice cultivars under irrigated DSR systems.
- **ix.** Assessing the economic tradeoffs of using crop residue as mulch for weed suppression vs its alternate use as animal feed.
- **x.** Integrating preventive methods with curative methods for effective and economical weed management in DSR systems.

5. CONCLUSIONS

In DSR, weed management is more difficult and the potential yield losses due to weeds are much higher than in transplanted rice, resulting in increased dependence on herbicides for weed control in DSR systems. Sole herbicide-based weed control is not sustainable and has environmental and human health implications. Therefore, to manage weeds effectively and sustainably, it is essential to develop and deploy flexible integrated weed management practices, with more emphasis on preventive and cultural methods to reduce dependence on herbicides in DSR systems. However, information on preventive weed management in DSR is relatively limited. Based on this review, key preventive weed management approaches relevant for DSR are summarized as follows:

i. *Minimizing weed seed production* in the field is critically important for managing weed seedbanks in DSR. However, given seed dispersal both in time and space, the prevention of seed production from neighboring bunds, rice–fallow land, and irrigation channels bordering DSR areas may be equally important. One possible approach to minimize seed production in neighboring areas and rotational fields is to grow cash crops, fodder crops, or smother crops to suppress weeds. The extra-initial costs associated with reducing weed seed rain may be offset by lower weed management costs in future years.

ii. *Preventing or minimizing dispersal* of weed seeds may be a practical approach for species that are dispersed primarily by humans [e.g., as contaminants in crop seeds or manures, or through agricultural implements (e.g., tractors, seed drills, combine harvesters), and irrigation canals], but not for species that are dispersed primarily by other means (wind, birds, etc.). Therefore, understanding the relative importance of seed dispersal mechanisms of key weeds of DSR is an important first step for developing strategies for dispersal prevention. For species that are primarily dispersed by humans, proactive management practices that may help minimize weed seed dispersal include strategies to minimize weed seed contaminants in crop seeds (e.g., modifying the harvest and thresher equipment to avoid and separate weed seeds or using certified seeds); sanitizing the planting and harvesting equipment; filtering irrigation water flow at entry points with nylon nets; and adjusting composting to ensure lethal temperatures for weed contaminants.

iii. *Promotion of seed predation* may be a useful strategy for managing weeds, particularly in ZT-DSR, but many knowledge gaps remain. Current evidence suggests that rates of seed predation on the soil surface can be very high in rice cropping systems, but little is known about the identity of seed predators or management factors that might promote their activity. Crop management strategies that enhance weed seed exposure to predators (e.g., zero-tillage or delayed tillage); create refuges for known predators (e.g., bund management, residue retention); or reduce seed-predator mortality (e.g., adjustments in insecticide use or irrigation timing) all hold promise for enhancing the activity of seed predators while also providing other pest-regulating services.

iv. Available evidence suggests that the potential for *promotion of seed decay* is limited in scope but may be valuable for the management of certain relatively nonpersistent weeds in some cropping systems. Information on weed seed decay in DSR ecosystems is meager. Strategies that promote weed seed decay by promoting indigenous microflora—such as changes in flooding timing and duration or addition of biologically active soil amendments—may have potential to selectively promote weed seed decay in DSR cropping systems, but more research is needed to economically apply these approaches.

v. Strategies that *stimulate fatal germination* of weed seeds appear to be one of the most promising means of prevention in DSR. The stale seedbed practice is currently an effective preventive strategy in many cropping systems and increased information on the mechanisms and timing of dormancy release for key species will likely enhance the value of this approach.

vi. *Prevention of weed germination and emergence* in DSR through mulching and flooding has been demonstrated in many studies to be an effective strategy for preventive weed management. However, mulch retention is less practical in regions where mulches have economic value as feed for livestock, or where specialized equipment for planting through residue is not available. Currently, early season flooding is not a viable option for DSR. However, the development and use of rice cultivars which can tolerate anaerobic conditions/flooding at germination can facilitate the use of early flooding for weed control in DSR systems.

Successful integration of preventive approaches to managing weeds in DSR will depend on the targeted evaluation of approaches which are biologically effective, economically feasible and socially acceptable. Toward that end, collaborations between weed scientists and experts in both the natural and social sciences will be essential for successfully integrating preventive approaches to managing weeds in DSR. Preventive weed control measures alone are unlikely to be sufficient for effective and economical management of weeds in DSR systems, but their integration with curative approaches should reduce weed management costs and increase the likelihood of adoption of DSR, as well as the realization of its benefits for food security.

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