Weed management in direct-seeded rice systems

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IRRI

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Foreword

Rice is an important crop in Asia, where it is mainly grown by manual transplanting of seedlings after land preparation under wet conditions. Recently, farmers in many Asian regions have been shifting to direct-seeded rice systems because of high labor costs and less availability of water. There has been a continuous migration of laborers from rural areas to cities. In the future, many farmers may have limited availability of water to flood their rice fields. There are mainly two kinds of direct-seeded systems practiced in Asia: dry- and wet-seeded rice.

Direct-seeded rice systems have several advantages. Weeds, however, are considered one of the major biological constraints in these systems because there is no seedling size advantage as rice and weed seedlings emerge simultaneously and no standing water to suppress weed emergence and growth at crop emergence. Weeds in direct-seeded systems can cause a substantial rice yield loss. Weeds are mainly controlled using herbicides or are manually controlled. However, manual weeding is becoming less common because of the nonavailability of labor at critical times and increased labor costs. Herbicides are replacing manual weeding as they are easy to use; however, there are concerns about the sole use of herbicides, such as evolution of resistance in weeds, shifts in weed populations, and concerns about the environment.

There is a need to integrate different weed management strategies to achieve effective and sustainable weed control in direct-seeded rice systems. This publication describes different strategies, including preventive and cultural approaches, to manage weeds in these systems. This information will help researchers and extension specialists to develop integrated weed management programs for direct-seeded rice systems.

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Weed management in direct-seeded rice systems

Rice is an important source of food for more than half of the world population. About 90% of the total rice is grown and consumed in Asia. In most Asian countries, rice is grown by manual transplanting of seedlings into puddled soil. Puddling is achieved by intensive soil tillage under wet conditions. The puddling operation creates a hard pan below the plow layer and reduces soil permeability. However, this operation leads to high losses of water through surface evaporation and percolation. Furthermore, puddling deteriorates soil structure and soil quality for the subsequent upland crops, such as wheat. Puddling and transplanting operations consume a significant quantity of water; in some cases, up to 30% of the total rice requirement (Plate 1).

About 55% of the total rice area is irrigated and concerns are increasing about the availability of water for crops due to competition with urban areas. In the future, farmers may have limited availability of water to flood their rice fields and most of the areas in South and Southeast Asia may suffer from physical and/or economic water scarcity. Transplanting is usually performed by rural labor; however, there are concerns about labor availability because of the increasing costs of labor resulting from the migration of rural labor to the cities. In many areas, it is difficult to find labor at the critical time of transplanting, resulting in transplanting of old seedlings and a reduction in yield.

Because of the decreased availability of water and/or labor and increased production costs, farmers in many Asian countries have been or are shifting from manual transplanting to direct-seeded rice systems or mechanical transplanting. There are mainly three kinds of direct-seeded rice systems: dry-seeded, wet-seeded, and water-seeded. Water seeding is mainly practiced in the U.S. and some parts of Asia. Because of the nonavailability of rice cultivars tolerant of anaerobic soil conditions, this seeding system is not practiced widely in Asia. However, research at the International Rice Research Institute (IRRI) is in progress to find suitable rice cultivars that are tolerant of anaerobic soil conditions for separate regions. In dry-seeded rice systems, dry rice seeds are sown into a prepared seedbed after land preparation or under zero-till conditions (Plate 2). In some areas, where seeding drills are not available, dry seeds are broadcast and then mixed by a light harrow. Depending on water availability, soils in dry-seeded rice systems are kept aerobic, continuously saturated, or flooded; however, there is a yield reduction

Plate 1. Puddling and transplanting operations consume a significant amount of water.

Plate 2. Dry-seeded systems: In these systems, dry rice seeds are sown into a prepared seedbed after land preparation (tillage) or under zero-till conditions.

in aerobic rice systems compared with systems in which soils are kept flooded. In wet-seeded rice, pregerminated rice seeds are broadcast or sown using a drum seeder onto a puddled soil surface (Plate 3). Most of the wet-seeded rice area is sown using the broadcasting method. Direct-seeded rice, especially dry-seeded rice, has many advantages over puddled-transplanted rice. Dry-seeded rice systems are more rapidly and easily planted, less labor intensive, consume less irrigation water, mature earlier, are conducive to mechanization, and have fewer methane emissions.

Direct-seeded rice systems, however, are not without critics. Weeds are the number-one biological constraint to the production and adoption of direct-seeded rice systems. The risk of greater crop yield losses due to weed competition in direct-seeded rice systems than in transplanted rice is mainly because of the absence of the seedling size differential between rice and weeds and the absence of the suppressive effect of standing water on weed emergence and growth at crop emergence time. Weeds in different direct-seeded systems can cause rice yield losses of up to 50% and these losses are after one hand weeding (or partial weed-free conditions) in weed-infested fields. In Asia, manual weeding and/or herbicides are commonly used to control weeds. However, manual weeding is becoming less common in

Plate 3. Wet-seeded systems: In these systems, pregerminated rice seed can be sown using a drum seeder onto a puddled soil surface.

many Asian countries because of the nonavailability of labor at critical times and increased labor costs. Manual weeding can be performed only when weeds have reached a sufficient size to be pulled out easily by hand. By that time, yield losses may have already occurred. Some weed species, for example, *Echinochloa colona* and *E. crus-galli*, are difficult to distinguish from rice at the early stage and they escape hand weeding, reduce rice yield, and produce seeds to infest crops in subsequent seasons. For these reasons, herbicides are being promoted to control weeds and they are easy to use. However, there are concerns about the sole use of herbicides, such as evolution of resistance in weeds, shifts in weed populations, less availability of new broad-spectrum herbicides, and concerns about the environment. Therefore, there is a need to integrate herbicide use with other management strategies to achieve effective, long-term, and sustainable weed control in direct-seeded rice systems. Data on rice yield losses due to weed competition suggest that there is considerable scope to reduce the yield gap in direct-seeded systems with integrated weed management strategies.

Weed management strategies

Various weed management strategies are available and, depending on the location and available resources, there is a need to include as many strategies as possible. Some of the strategies discussed below are applicable for only dry-seeded rice systems and others are applicable to both (dry and wet) seeding systems.

Preventive measures

The first and the most important weed management approach in any crop is the use of clean crop seed. Rice seeds infested with weed seeds may introduce problematic weed species to a new field and increase the seed numbers in the soil weed seed bank. In many countries, for example, weedy rice or red rice spreads through the distribution of contaminated rice seeds to farmers and now this weed has become a menace because of the nonavailability of selective herbicides to control it. In addition to clean crop seed, the machinery used for tillage, sowing, harvesting, or threshing operations should also be cleaned before moving it from one field to another. Bunds and irrigation canals free from weeds may also help to reduce the spread of weed seeds through irrigation water.

Stale seedbed technique

The stale seedbed technique is another important weed management strategy that can be used before any crop to reduce the weed seed bank. In the stale seedbed practice, weeds are allowed to germinate by giving a light irrigation (or after rainfall) and thereafter the emerged weed seedlings are killed by using a nonselective herbicide (glyphosate or paraquat) or shallow tillage (Plate 4). Compared with nonselective herbicide application, however, the tillage will stimulate further weed seedling emergence as buried weed seeds are exposed to light and light is known to stimulate weed seed germination. The best way to use the stale seedbed practice is to prepare the field in advance and then stimulate weed emergence by irrigation, kill the emerged seedlings using nonselective herbicides, and plant the crop without further tillage operations. In this way, there will be only a few weeds in the crop as most of the weed seedlings emerged in the top 2-cm soil layer. However, protracted emergence of some weed species may occur due to different kinds of dormancy present in different weeds. Regardless of the method (herbicide application or tillage), use of the stale seedbed practice would reduce the weed seed bank in the soil. Most weed species conducive to be controlled by this practice are those that have low initial

Plate 4. Stale seedbed practice: In this practice, weed seedlings are allowed to emerge after light irrigation and then killed by nonselective herbicide application or tillage.

dormancy and are present in the top soil layers, such as *Leptochloa chinensis*, *Eclipta prostrata*, *Digitaria ciliaris*, and *Ludwigia hyssopifolia*. The use of the stale seedbed practice could also help reduce the problems of hard-to-control weeds, such as *Cyperus rotundus*, weedy rice, and volunteer rice seedlings. Although this practice is very useful in reducing weed populations, the practical possibility of this practice needs to be evaluated by farmers themselves when the period between the harvesting of the preceding crop and sowing of the next crop is short and when crop intensification is the main aim of the farming.

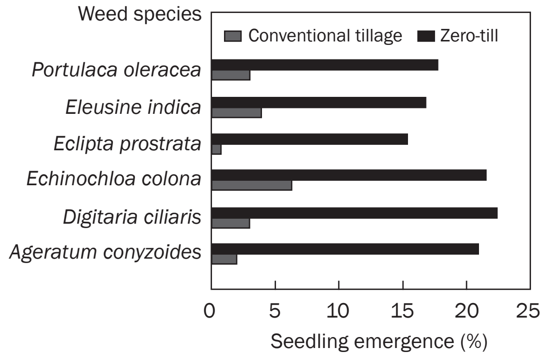

Fig. 2. Effect of tillage systems on seedling emergence of different weed species under aerobic rice systems.

Tillage systems

Dry-seeded rice can be sown under zero-till or reduced-till conditions, or after thorough land preparation. Soil disturbance during land preparation or sowing operations influences vertical weed seed distribution in the soil profile and this distribution has the potential to influence weed seedling emergence. Low soil-disturbance systems, for example, zero-till systems, retain most of the weed seeds in the top soil layer, whereas high soil-disturbance systems thoroughly mix the weed seeds within the cultivation layer (Fig. 1). Therefore, low soil-disturbance systems will leave most of the weed seeds on or near the soil surface.

The conditions required for germination are usually more suitable for the seeds present near the soil surface than when they are buried deep in the soil. In the initial stage of adoption of zero-till systems, greater emergence of some weed species can be expected compared with conventional tillage systems and this response could be due to the light requirement for germination and small seed size of the weeds (Fig. 2). In the long run, however, zero-till systems can help in reducing the weed seed bank if weeds are effectively controlled in crops. In zero-till systems, soil is not disturbed and therefore buried weed seeds are not brought to the soil surface. In addition, weed seeds present on the soil surface under zero-till systems are prone to rapid desiccation and predation by insects, and are sensitive to the stale seedbed practice.

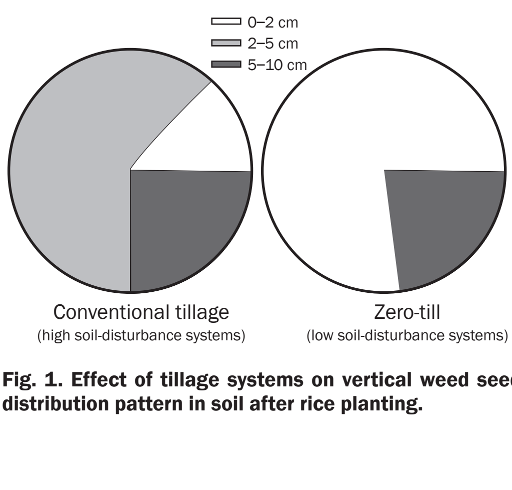

Fig. 1. Effect of tillage systems on vertical weed seed distribution pattern in soil after rice planting.

In continuous zero-till systems, a large amount of weed seeds may accumulate on the soil surface. In such situations, an off-type deep tillage operation could be used to bury weed seeds below the maximum depth of their emergence. Although maximum depth of emergence varies among species, most of the weed species in rice cannot emerge if buried deeper than 6–8 cm. Where direct-seeded rice is sown after tillage, land is prepared thoroughly for seedbed preparation and killing of emerged weed or volunteer crop seedlings, and, depending on the direct-seeding systems, tillage is performed in dry (for dry-seeded rice) or wet (for wet-seeded rice) soil conditions. Good land preparation helps in reducing weed densities by providing a weed-free seedbed at the time of crop sowing. To achieve uniform plant stands, the field should be laser-leveled before crop sowing. Leveling is usually done by using a wooden/metal board (Plate 5); however, such fields have frequent dikes and ditches, which result in poor crop emergence and poor weed control. Recently, farmers in South Asia (e.g., India) and Southeast Asia (e.g., Cambodia)


Plate 5. Land leveling using metal board and laser land leveling.

have been adopting laser land leveling (Plate 5). Laser land leveling results in better crop establishment, water savings, energy savings, and improved weed control and nutrient-use efficiency. Different direct-seeded systems can be rotated to reduce weed problems. Buildup of weed populations in wet-seeded rice, for example, can be suppressed by rotating to dry-seeded rice (zero-till or after tillage) and vice versa.

Weed-competitive cultivars

The choice of a cultivar plays an important role in crop-weed competition due to the cultivar's morphological characters and the competitive ability of rice is usually associated with light interception-related traits (Plate 6). Tall and traditional cultivars with droopy leaves, for example, are superior competitors to short-statured modern cultivars with erect leaves, but tall cultivars often have lower yield potential. Therefore, there is a trade-off between yield potential and competitive ability and this trade-off could be minimized by selecting competitive traits other than plant height. Tall plant type may not be considered as a desirable trait in future rice systems because there will be more nitrogen use to meet the increasing food demand and high nitrogen rates are known to cause lodging in tall plant types.

In the absence of suitable weed-competitive cultivars, cultivars with early emergence and early vigor traits could be used as a preventive weed control measure in direct-seeded rice systems. The main aim of using weed-competitive cultivars should be to achieve rapid canopy closure so that shade under the canopy would suppress the growth of weeds. Hybrids usually have better vigor than inbreds; therefore, when possible, hybrids can also be used in direct-seeded systems. However, hybrids are used at low seeding rates (e.g., 15 to 20 kg ha^{-1}) because of their expensive seeds. In direct-seeded systems, the use of weed-competitive cultivars would be integrated with at least one application of preemergence or early postemergence herbicide. The idea is that the use of herbicide would provide effective weed control at the early stage and then traits of weed-competitive cultivars would help in suppressing weed growth at the later stages. Therefore, it is impor-

Plate 6. Rice cultivars with different weed-competitive traits.

tant that a weed-competitive cultivar have the traits that can make the crop more competitive at its later stage. In rice, especially in direct-seeded systems, compared with aboveground traits, very little attention has been given to the role of root competition for nutrients and water in rice-weed interactions. There is a need to include both aboveground and belowground traits when examining rice-weed interactions.

High seeding rates

In many countries, high seeding rates are used in direct-seeded rice systems. Farmers use high seeding rates mainly to compensate for poor seed quality and poor crop emergence as they use their own-stored seeds and to compensate for losses due to rodents, birds, insects, nematodes, and snails. In addition, the use of high seeding rates can also help in suppressing weed growth; however, the effectiveness of high seeding rates in suppressing weed growth depends on the biology of the weeds present as well as that of the rice cultivar used. In weed-free environments, grain yield may remain similar at low and high seeding rates, for example, from 25 to 125 kg seed ha^{-1} (Fig. 3). In the presence of weeds, however, grain yield may increase with increasing seeding rates. In addition, increasing seeding rates may also help in reducing weed growth (Fig. 4). High seeding rates result in rapid canopy closure and reduce weed competition. In conclusion, high seeding rates may help to suppress weed growth and reduce grain yield losses due to weeds if no or partial weed control is expected.

The use of high seeding rates in humid environments might exacerbate problems detrimental to grain yield, such as nitrogen deficiency, increased numbers of unproductive tillers, insect and disease infestations, and crop lodging. In some countries, for example, India, farmers use hybrids or buy new seeds of inbred cultivars. In such conditions, farmers cannot use high seeding rates because of the high cost incurred for seeds. Because of the availability of suitable sowing drills or planters with precise seed-metering devices (Plate 7), seeding rates of only 15 to 25 kg ha^{-1} are used for sowing dry-seeded rice crops. However, to achieve uniform plant stands at low seeding rates, it is important to have good-quality seed with a high germination percentage, a laser-leveled seedbed, optimum sowing depth, and optimum moisture. In addition, losses due to birds, rats, insects, nematodes, and snails should be eliminated. The use of such low seeding rates is still in question in Southeast Asia. Before suggesting low seeding rates in direct-seeded systems, there is a need to test low seeding rates using suitable seed drills in farmers' fields in various countries in South and Southeast Asia.

Row seeding in narrow spacing

Because of the nonavailability of suitable seeding drills and very small field size, farmers in many Asian regions broadcast rice seeds at very high seeding rates and this is true for both dry- and wet-seeded rice. Although the use of

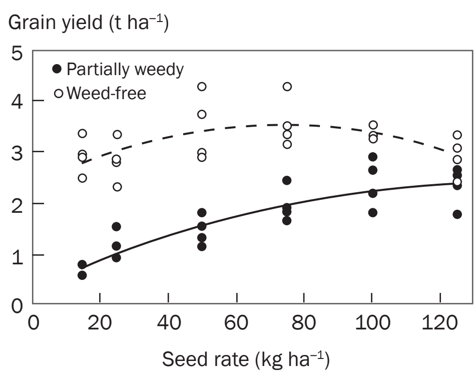

Fig. 3. Effect of seeding rate on rice grain yield under partially weedy (one hand weeding) and weed-free conditions in aerobic dry-seeded rice systems in the Philippines.

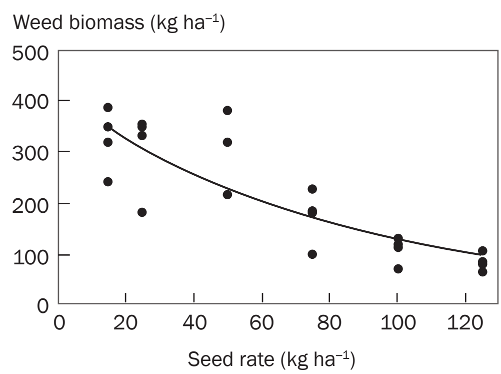

Fig. 4. Effect of seeding rate on weed biomass in aerobic dry-seeded rice systems in the Philippines.

Plate 7. Seed-metering systems used for dry seeding of rice.

Plate 8. Direct-seeded rice crops can be sown as broadcast or in rows.

high seeding rates in a broadcast crop improves the crop's competitiveness with weeds by developing faster canopy cover and allowing less light penetration through its leaves, it is difficult to perform mechanical or manual weeding in broadcast crops. In broadcast crops, it is difficult to distinguish some weed species, such as weedy rice, *E. colona*, and *E. crus-galli*, from rice plants at the early stage and therefore such weed species escape manual weeding and, as a consequence, reduce crop yield. In addition, a broadcast rice crop is more prone to lodging due to heavy winds than a row-seeded crop because there is no passage of wind in the broadcast crop. Therefore, a direct-seeded crop sown in rows will have an advantage over a broadcast crop as a crop grown in rows will allow farmers to practice interrow cultivation (Plate 8). This practice will be very helpful in weedy rice-infested areas, for which there are no selective herbicides in rice. In row-seeded crops, weedy rice emerging between the rows can be distinguished and pulled out.

Within row-seeded direct-seeded crops, narrow row spacing should be used to obtain rapid canopy closure. In wider row spacings, however, it is easy to perform mechanical weeding. In weed-free environments, the grain yield may be similar between a crop planted with 20-cm or 30-cm row spacing. In weedy or partially weedy conditions, however, higher grain yield is obtained in narrow row spacing than with wider row spacing. Seed-sowing drills are capable of seeding at 18- to 20-cm row spacing and therefore farmers in South Asia are already growing dry-seeded rice at narrow row spacing. The critical periods for weed control are usually less for crops planted in narrow rows

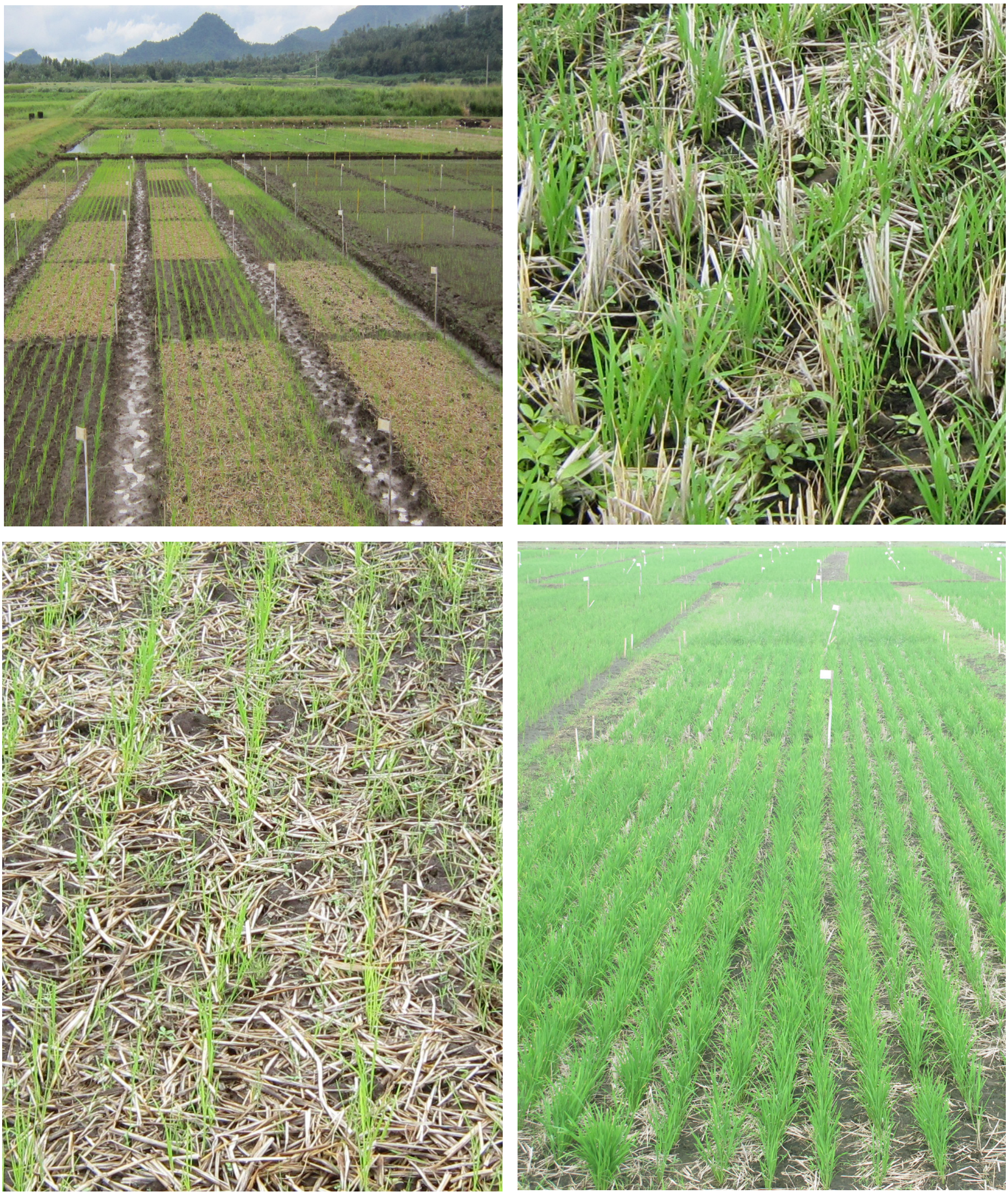

Plate 9. The use of residue as mulches can help in suppressing weed emergence and weed growth in dry-seeded rice systems.

than for crops planted in wider rows (Fig. 5). In addition, weeds grown in wider rows may have greater biomass than weeds grown in narrow rows (Fig. 6). Therefore, a direct-seeded crop should be grown using narrow row spacing to obtain faster canopy closure and less penetration of light and ultimately less weed growth. The use of paired-row patterns (e.g., 20-10-20 cm or 25-15-25 cm) may also enhance the weed competitiveness of some rice cultivars. At the moment, however, such practices are mainly in the research phase.

Use of crop residue as mulches

Crop residue present on the soil surface not only improves soil and moisture conservation but can also influence weed seedling emergence and weed growth. However, the response of weeds to residue depends on many factors, including the quantity and position of weed seeds relative to the residue, the allelopathic potential of the residue, and the biology of the weed species. For example, rice residue in rice-rice or rice-rice-rice cropping systems, wheat residue in the rice-wheat cropping system, maize residue in the rice-maize cropping system, etc., may influence weed seedling emergence and weed growth differently in direct-seeded rice systems and these differences could be due to the thickness of the residue in the field, weed seed depth in the soil, soil type, and allelopathic potential of the crop residue. As rice seeds are usually larger than most of the weed seeds, the use of residue as mulches can help in suppressing weed emergence in direct-seeded systems (Plate 9). Seedlings of many weed species can be suppressed by using crop residue as mulches (Fig. 7).

In some areas, where time is sufficient between two crops, legume crops, such as sesbania or mungbean, can be used to reduce the weed population. These crops are killed by using nonselective herbicides and their residue may not only help in suppressing weed emergence but also add fertility to the soil. Some of these legume crops can produce up to 25 t ha^{-1} of green biomass within 60 days. In addition to reducing the number of weed seed-

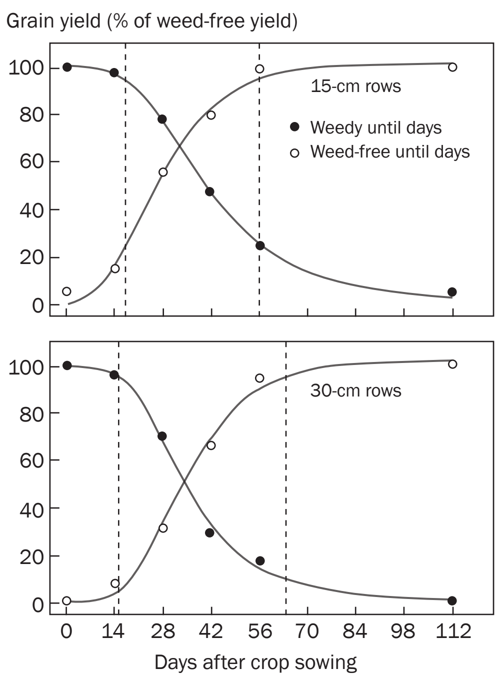

Fig. 5. Effect of row spacing and different periods of weed competition on rice grain yields under aerobic dry-seeded rice systems in the Philippines. The period between the broken vertical lines is the critical weed-free period to achieve 95% of maximum yield.

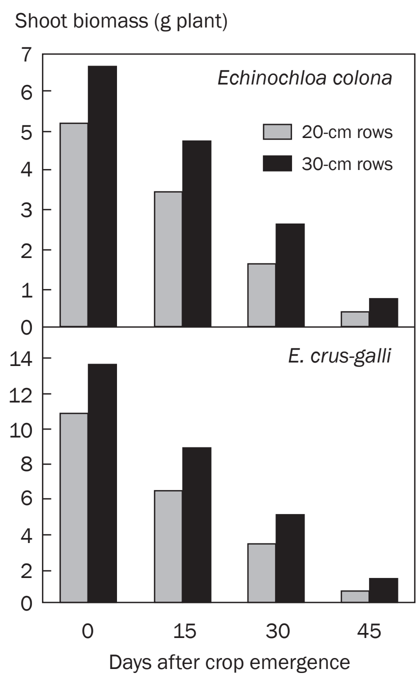

Fig. 6. Effect of rice row spacing and weed emergence time (days after crop emergence) on biomass of *Echinochloa colona* and *E. crus-galli*.

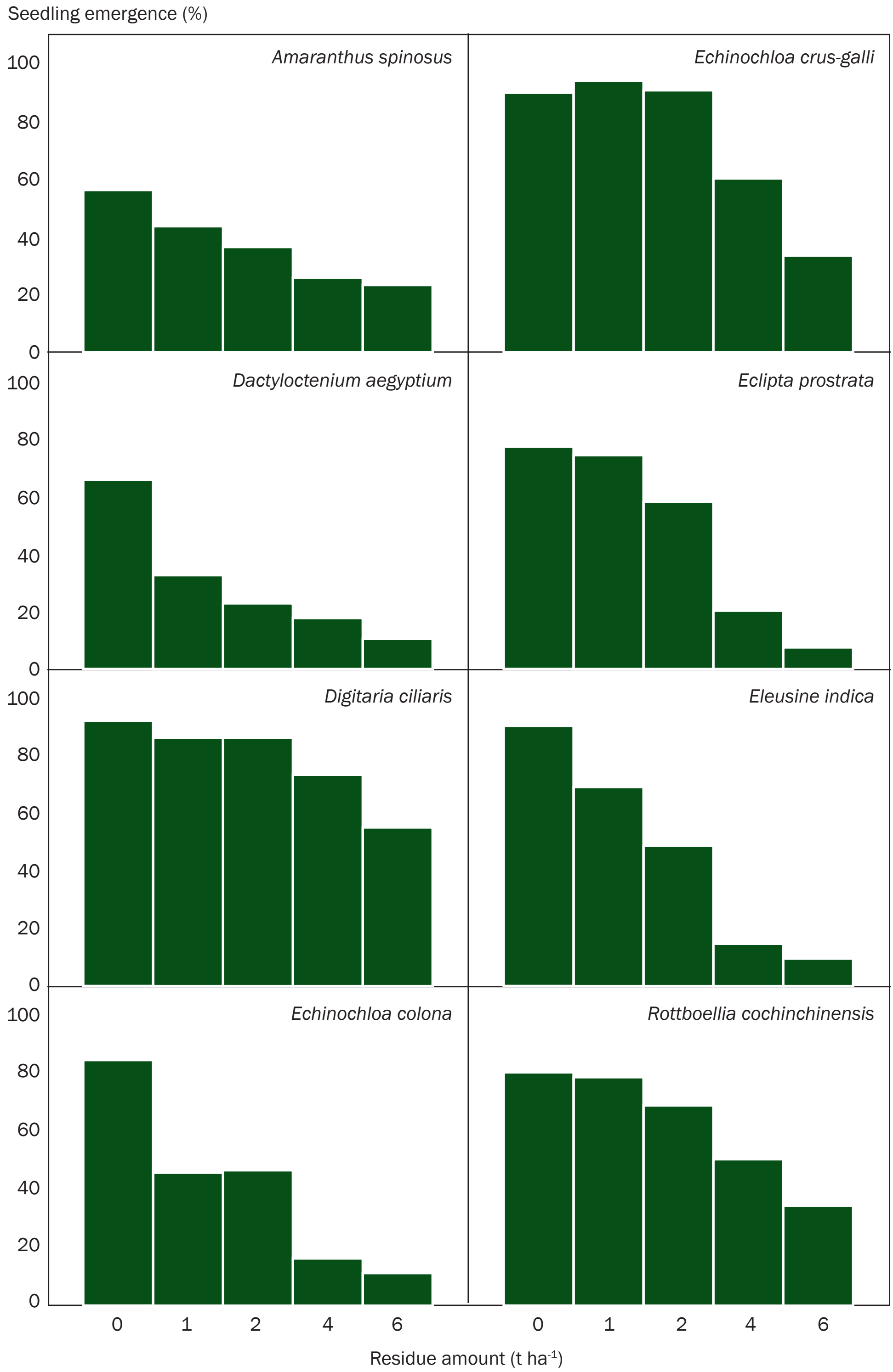

Fig. 7. Effect of rice residue amount on seedling emergence of different weed species.

lings, high amounts of residue can also delay emergence by preventing light penetration into the residue. This delayed weed emergence may have implications for weed management. This could mean that late-emerging seedlings would be less competitive to the crop and likely have less impact on crop yield loss and weed seed production. The delayed or protracted emergence could also mean that the late-emerging seedlings may escape the application of early postemergence herbicides. In many Asian regions, farmers burn their crop residue in the field. The use of rice straw as mulches may become very relevant in the future in these areas because of concerns about environmental pollution and depletion of soil organic matter after straw burning. In conclusion, retention of crop residue in zero-till dry-seeded rice systems can suppress the emergence and growth of many weed species. Seeding drills capable of planting in high residue cover are available in some countries (Plate 10); however, there is still scope for further improving the efficiencies of these drills for both small- and large-scale farmers.

Water management

Water, as flooding, has been known as the most effective weed control tool in rice. As mentioned earlier, direct-seeded rice can be grown under different water regimes. Farmers in some areas have plenty of water and they can flood their fields throughout the crop season after crop emergence. This is mostly relevant to wet-seeded rice in which puddling helps to retain water. In light-textured soils, water may not remain standing in the field. In other soils, too, water may drain quickly because there is no hard pan to retain water in dry-seeded systems. In such soils, it is difficult to keep rice fields flooded continuously. Furthermore, many rice farmers in the future may have limited water, which would reduce their capacity to use continuous flooding as a weed control mechanism. In such situations, flooding after manual weeding or herbicide application could largely prevent the subsequent emergence and growth of weeds (Plate 11). The timing, duration, and depth of flooding should be optimum to effectively manage weeds.

Plate 11. Flooding after herbicide application or hand weeding can suppress subsequent growth of weeds in direct-seeded systems.

Plate 10. Seed drills capable of seeding in high residue amounts.

At present, flooding is introduced in direct-seeded fields only after crop emergence as rice cultivars tolerant of anaerobic conditions are not widely available in Asia. By the time fields are flooded, weeds may have already emerged and then they become difficult to suppress by flooding. Work on anaerobic-tolerant rice cultivars is in progress at IRRI and the availability and use of such rice cultivars will prove very useful in managing weeds with reduced herbicide use.

Mechanical weeding

Although mechanical weeding using hand-pushed weeders (e.g., cono weeder) is tedious and time-consuming, it is common in many rice-growing areas (Plate 12). The use of mechanical weeders is feasible only where rice is planted in rows; however, weeds emerging within rows are difficult to remove with these weeders. The soil moisture is very critical to achieve best results using weeders. Where farmers use mechanical weeding, hand pulling of weeds within rows is necessary.

Plate 12. Mechanical weeding.

Herbicides

Herbicides are one of the most important tools for managing weeds in direct-seeded rice systems. Herbicide use in these systems is expected to increase in the near future because of the nonavailability of labor at the critical time of weeding and high labor cost. Herbicide use is also very important where there is a morphological similarity between weeds and rice, especially in a broadcast crop.

Depending on the country, various pre- and postemergence herbicides are recommended and used in direct-seeded systems. Some of the preemergence herbicides for dry-seeded rice systems are oxadiazon, oxadiargyl, and pendimethalin. As rice seeds are broadcast on the soil surface in wet-seeded rice, pretilachlor (with safener) is usually recommended as a preemergence application. To achieve effective weed control, the use of preemergence herbicides is a must in direct-seeded systems, especially in dry-seeded ones. Some preemergence herbicides (e.g., oxadiazon), however, can be phytotoxic to crop emergence if heavy rain occurs immediately after herbicide application (Plate 13). This could be a serious problem where farmers use very low seeding rates. Therefore, in such situations, early postemergence herbicide application should be preferred. Postemergence herbicides are similar between dry- and wet-seeded rice systems

Plate 13. Heavy rain or standing water after oxadiazon application may result in a phytotoxic effect on crop emergence.

and some of these herbicides are bispyribac, fenoxaprop, penoxsulam, azimsulfuron, cyhalofop, ethoxysulfuron, metsulfuron, 2, 4-D, and their commercial mixtures. Postemergence herbicides should be used very wisely at the appropriate weed stage and appropriate herbicide dosage. There is also a need to observe the weed species before herbicide application. *Dactyloctenium aegyptium* and *L. chinensis*, for example, are less affected by bispyribac application; therefore, fields dominated by these weed species should not be sprayed with bispyribac.

Because of the broad range of weeds in direct-seeded systems, especially in aerobic rice systems, there is a need to use mixtures of different compatible herbicides. Even after using herbicide mixtures, some weed species are not controlled effectively. Furthermore, because of their high seed dormancy, some weed species (e.g., *Rottboellia cochinchinensis*) keep emerging throughout the crop season. Therefore, a hand weeding should be performed to get rid of escaped weed species. Where farmers integrate herbicide use with other weed management strategies, such as high seeding rates, there may not be a need for hand weeding. However, a direct-seeded crop sown at low seeding rates or using hybrids may need one hand weeding as canopy closure in such crops takes a longer time.

In the modern era, the use of herbicide-resistant crops is increasing. Nontransgenic herbicide-resistant rice cultivars may gain popularity in the near future where weedy rice is becoming a problem in direct-seeded rice systems. No selective herbicide controls weedy rice in a rice crop and therefore the use of herbicide-resistant rice cultivars may manage weedy rice and other problematic weeds very effectively. However, without good "stewardship," their widespread use may threaten the sustainability of direct-seeded rice production in Asia. Before introducing such cultivars in different Asian countries, there is a strong need to develop effective and sustainable stewardship guidelines for their use. In addition, there is a need to identify risk management strategies for gene flow (from herbicide-resistant rice to weedy or wild rice), drift risks, and the development of herbicide-resistant weed populations.

As herbicide use is expected to increase in the future, it is very important to understand the right application methods for herbicides. Improper and ineffective methods of herbicide application may result in damage to nontargeted plants; a great waste of chemicals, resulting in environmental pollution; and negative effects on human health. Herbicides can be sprayed using a knapsack, foot sprayer or pedal pump, and tractor-mounted and aerial sprayers; however, knapsack sprayers are the most popular in Asia. Various kinds of spray nozzles are used, including a flat fan, even fan, flood nozzle, variable cone, and hollow cone (Plate 14). Flat fan nozzles are used in multiple-nozzle booms as the spray pattern is tapered from the center to the edges (Plate 15). Such patterns help to create a uniform coverage through overlapping with adjacent nozzles. Flood nozzles provide a wide spray pattern at low pressure and therefore they are very popular among farmers. They are suitable

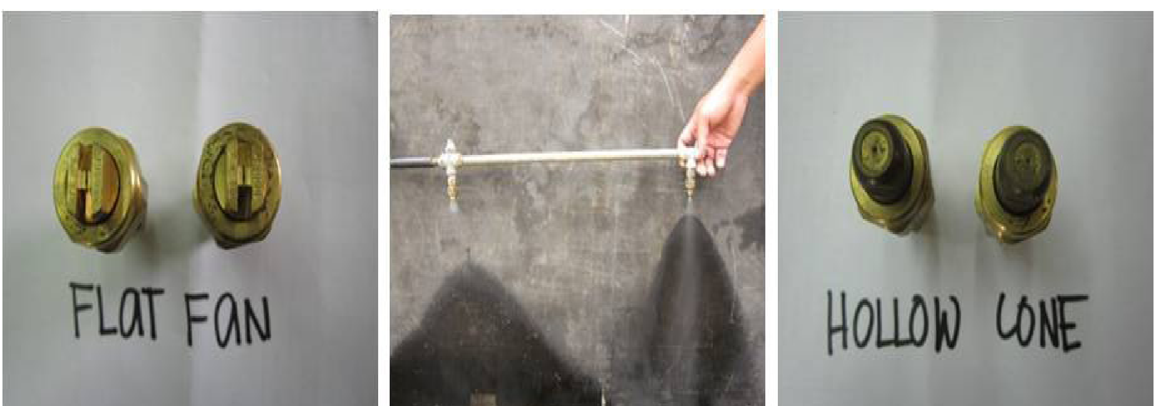

Plate 14. Flat fan and hollow cone nozzles.

Plate 15. Spray of a preemergence herbicide using flat fan tips in multiple-nozzle booms.

where multiple-nozzle booms are not used and when using nonselective herbicides. Using these nozzles in a “swinging” way across the spray site, however, may result in poor weed control.

Multiple-nozzle booms are used to increase the efficiency and accuracy of herbicide application (Plate 15). Flat fan nozzles are used in multiple-nozzle booms and nozzles on the boom are uniformly spaced (50 cm apart) such that the spray pattern of the adjacent nozzle would overlap by 30%. On the boom, 3–4 nozzles can be placed and one person can spray easily. If two people are available, the width of the boom can be up to 5 m (Plate 15). With a multiple-boom sprayer, every spray pass will have a very uniform herbicide distribution. The height of the boom is very critical when using a multiple-nozzle boom. While spraying, it is very important to wear boots, long trousers, rubber gloves, and goggles. It is strongly advised not to drink, eat, or smoke while handling any pesticides, including herbicides.

Integrated weed management strategies

Several weed management strategies for direct-seeded rice systems were discussed in the previous sections (Fig. 8). The use of any single strategy cannot provide effective, season-long, and sustainable weed control as different weeds vary in their dormancy and growth habit. Based on the available resources and kind of direct-seeded systems, combinations of as many strategies as possible would control weeds more effectively than with the use of one weed control strategy.

The available weed management strategies could be integrated in different ways. In zero-till systems, for example, the use of a stale seedbed practice followed by retention of crop residues followed by applications of early and late postemergence herbicides can substantially reduce weed densities in dry-seeded rice crops. The use of preemergence herbicides in residue-retained fields may result in lower efficacy for some weeds because the soil-applied herbicide might be adsorbed on the crop residue. However, such a response depends on water management and herbicide property. Another example of integrated weed management in dry-seeded rice sown after tillage is the use of a stale seedbed practice followed by crop sowing at high seeding rates and narrow row spacing followed by the use of pre- and postemergence herbicides. The use of integrated approaches is very important where direct-seeded rice is sown at

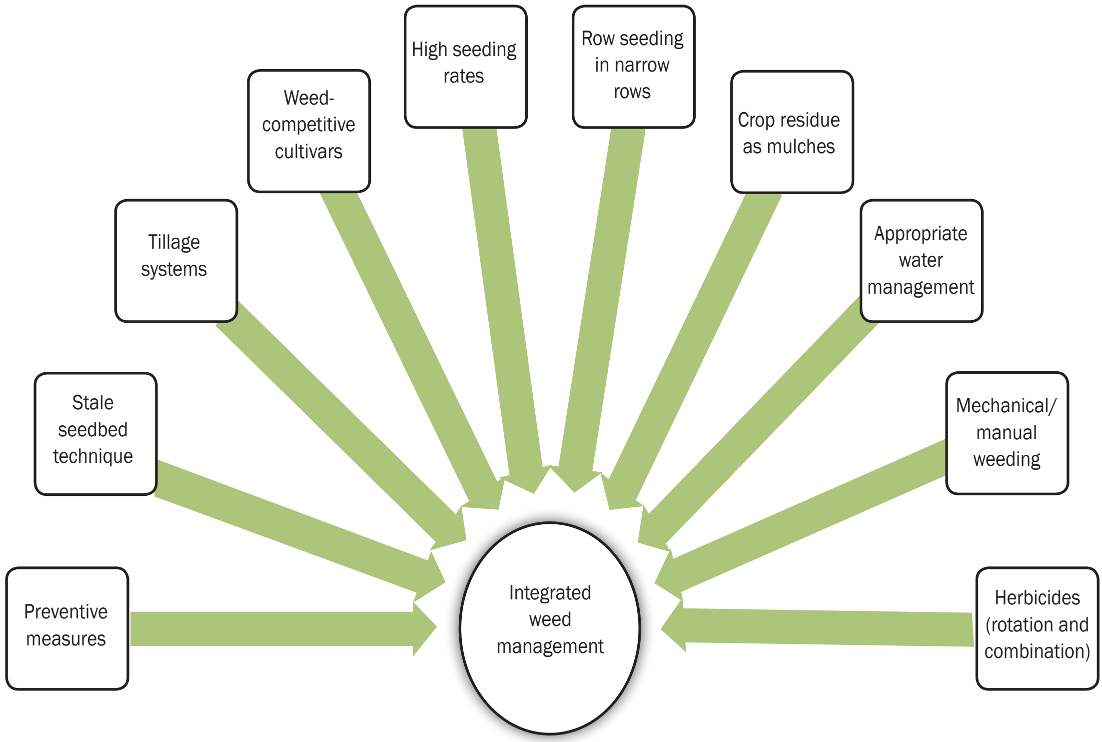

Fig. 8. Different weed management strategies for direct-seeded rice systems.

low seeding rates. In this case, the use of a stale seedbed practice followed by sowing at narrow spacing (18–20 cm) followed by the use of pre- and postemergence herbicides and flooding (if possible) followed by a hand weeding (if needed) could be very effective in managing weeds.

If possible, the use of a stale seedbed practice should be adopted in any system of direct-seeded rice. The main objectives of the weed management approaches should be to deplete the weed seed bank from the soil and enable the rice crop to be more competitive by either delaying weed emergence or suppressing weed emergence and growth. *Weeds are only a symptom of the problem; the main problem is the weed seed bank.* Therefore, every effort should be attempted to reduce the size of the weed seed bank in the soil.

Conclusions

The area under direct-seeded rice systems is expected to increase in the future because of labor and water shortages. Weeds, however, are the major constraints to direct-seeded rice production. To achieve effective, long-term, and sustainable weed control in direct-seeded systems, there is a need to integrate different weed management strategies, such as the use of a stale seedbed practice, the rotation of different direct-seeded systems, the use of crop residue as mulches, the use of weed-competitive cultivars with high yield potential, appropriate flooding depth and duration, appropriate agronomic practices (row spacing, seeding rates, and manual or mechanical weeding), and appropriate herbicide mixtures, timing, and rotation.

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