Anaerobic Direct Seeding of Rice in the Tropics*

Minoru YAMAUCHI

International Rice Research Institute (IRRI), P.O. Box 993, Manila, Philippines

Received May 1, 1995

Abstract

Rice farmers in the tropics practice direct seeding by broadcasting germinated seeds on the puddled soil surface. Constraints include inconsistent seedling establishment, heavy weed infestation, and lodging. To solve these problems, we developed an anaerobic seeding technology in which germinated seeds are broadcast or drill-sown under the surface of flooded or water-saturated soil. The coleoptile and mesocotyl elongated rapidly under anaerobic conditions during the successful establishment. Use of cultivars tolerant to anaerobic conditions and with high seed vigor improved and stabilized the anaerobic seedling establishment. The technology was useful not only in improving the seedling establishment but also in controlling weeds and increasing lodging resistance.

Additional key words : coleoptile, crop establishment, cultivar, lodging, seed aging, weeds.

Introduction

Farmers in the tropics are shifting rice crop establishment methods from transplanting to wet direct seeding. The shift is prominent in Malaysia, Thailand, Vietnam, the Philippines, and Myanmar. In wet direct seeding, the land is puddled in the same way as in the transplanting culture, and after 1-2 d, germinated seeds are broadcast on the soil surface with (water seeding) or without standing water (wet seeding). Farmers believe that seeds covered by wet soil develop poorly or die. Therefore, they broadcast the seeds on the soil surface.

Direct seeding is preferred by the farmers because it requires less labor and time than transplanting. In Malaysia, the shift from transplanting to direct seeding was mainly caused

* This report was written within the framework of the collaborative project between IRRI and JIRCAS entitled "Development of stabilization technology for rice double cropping in the tropics" sponsored by the Government of Japan.

Present address : Chugoku National Agricultural Experiment Station, Nishifukatsu 6-12-1, Fukuyama 721, Japan

by the labor shortage and spiraling transplanting cost as a consequence of the rapid economic growth[30]. In addition, grain yield of direct-seeded rice is reported to be the same as, or higher than, that of transplanted rice. The lack of transplanting damage in direct seeding is advantageous particularly for short duration cultivars. There are three major constraints, however, which have to be overcome soon for stabilizing grain yield and increasing adoption.

(1) Seedling establishment is inconsistent[12]. The causes include the destruction of seedlings by birds and rats and failure of rice seedling development due to factors associated with excess or deficiency of water. Because farmers sow seeds on the soil surface, bird and rat damages are serious.

The failure of rice seedling establishment needs to be clarified by analyzing the seed microenvironment and plant tolerance to abiotic and biotic stresses. Seedling growth might be optimum when seeds are placed between soil and atmosphere where O_2 and water are available. According to Chapman and Peterson[8], rice seeds can develop even in water using O_2 dissolved. When seeds are placed on the top of drained soil and the contact between seeds and soil is loose, the amount of water is insufficient for seed development. In addition, seedlings on the soil surface are flushed and are prone to lodging by heavy rain. On the other hand, when seeds are sown deep in the soil, the seedlings grow poorly or die[13].

Rice has an ability to germinate and develop a coleoptile in the absence of O_2. The root and leaf, however, do not develop in the absence of O_2 and the elongation of these organs depends on O_2 concentration[1]. There are differences among cultivars in coleoptile, root, and leaf development at low O_2 concentration[24], although the differences have not been analyzed in connection with seedling establishment. If we were to develop a technology in which seeds are sown under the surface of flooded or water-saturated soil (anaerobic seeding), damages caused by birds and rodents, water stress and rain-splashing could be avoided.

Coating seeds with a O_2-releasing chemical Calper (calcium peroxide) makes sowing into anaerobic soil possible[25]. Calper coating creates an aerobic environment around the seed. Because the coating technology requires additional work by farmers, including the purchase of Calper and a coating machine, it might be difficult to persuade farmers to adopt the technology.

(2) Weed infestation is more pronounced in direct-seeded ricefields than in transplanted fields[15]. Direct-seeded rice plants start to grow at the same time as the weeds, being exposed to heavier weed-competition than transplanted ones.

Herbicide use is most effective in weed control of direct-seeded ricefields. In addition, weed infestation can be reduced by intensive land preparation before sowing, improvement of seedling establishment and water control, increase of seeding rate, and use of weed-competitive cultivars. Drill seeding instead of broadcast seeding provides the opportunity for mechanical and manual weeding.

(3) Lodging is more common in direct-seeded rice than in transplanted rice. Because farmers are sowing seeds on the soil surface, plants are susceptible to culm-bottm type lodging[17]. In addition, high seed rate leads to high plant density, which induces bending-type lodging. Deep seeding and reduced seed rate are likely to increase the lodging resistance.

This study aimed at addressing these constraints. We identified germplasm accessions tolerant to anaerobic conditions (hereafter referred to as "anaerobic-tolerant") at the establishment stage, clarified the process of seedling growth, developed sowing methods, and incorporated these findings into the anaerobic seeding technology. Then, we determined how to integrate anaerobic seeding with water and tillage management to reduce weed infestation and lodging.

Germplasm tolerant to anaerobic conditions

An inexpensive, mass-screening system was developed to identify cultivars tolerant to flooded anaerobic conditions at the establishment stage[26]. Seeds that germinated for 2 d were placed on plastic seedling trays compartmentalized into 16×16×25mm with 17 rows×34 columns. One seed was placed in each compartment (Plate 1) and covered with 25mm of sieved soil. The tray was then submerged in water at 20-50mm depth (Plate 2). Percentage of seedling establishment, height, leaf development, and mesocotyl length were determined 15 d after planting (Plate 3).

We identified anaerobic-tolerant cultivars more frequently in aus (an early summer rainfed) and deepwater rice from Northeast India and Bangladesh (isozyme groups 2 and 3[11]) than in Indica (1) and Japonica (6) rice (Table 1). The cultivar group with less than 100 d growth duration showed a high selection percentage. Anaerobic-tolerant cultivars were also identified in improved semidwarf cultivars, *Oryza glaberrima*, and F_1 hybrid rice (Tables 1,2).

Anaerobic seedling development

Anaerobic-tolerant cultivars had a longer coleoptile than check cultivars in a gas flow of N_2 or air, or under various degrees of hypoxia induced in closed flasks[27]. In a flooded soil, the coleoptile of tolerant cultivars emerged above the soil surface more than that of the check cultivar (Fig. 1) Coleoptile emergence in the check cultivar was not followed by the 1st leaf emergence. These findings could be explained by the fact that coleoptile and mesocotyl of tolerant cultivars develop faster and longer than those of the check in soil under anaerobic conditions (Fig. 1).

The differences in seedling establishment between the cultivars and between the Calper-coated and noncoated seeds were large when the seeds were sown deeper (Fig. 2). Calper coating was more effective in promoting seedling establishment than the use of anaerobic-tolerant cultivars.

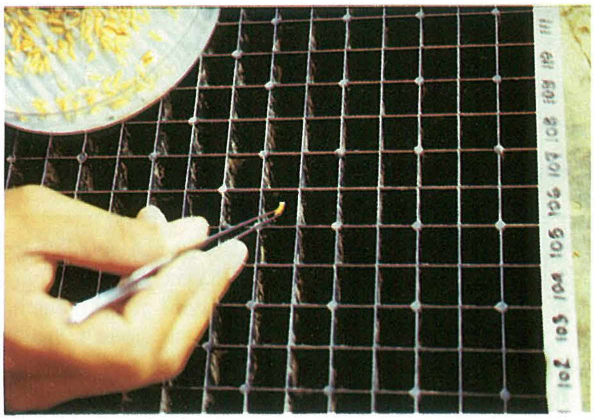

Plate 1. A germinated seed was placed at the bottm of a compartment, which was then filled with soil (mesh 40). The seeds of a cultivar were placed in a row per replication (17 compartments). The design was a randomized complete block with 4 replications.

Plate 2. The trays were submerged under 2-5 cm water for 15 d. Significant differences in seedling growth were detected among the culivars.

Plate 3. Seedling development after 15 d from a weak seedling with only coleoptile to a vigorous one with well developed roots and mesocotyl (left to right).

Table 1. Rice germplasm tolerant to flooded anaerobic soil conditions at seedling establishment. Materials were obtained from International Rice Germplasm Center (IRGC), International Network for Genetic Evaluation of Rice (INGER), and Plant Breeding, Genetics and Biochemistry Division, International Rice Research Institute (IRRI).

Screening number	Germplasm				Percentage
	Source	Specification	Number tested	Number selected	selection
1	IRGC	Isozyme group 1, Major group, Indica[1]	93	7	9
2	IRGC	Isozyme group 2, Minor group, Aus	29	5	17
3	IRGC	Isozyme group 3, Satellite, Deepwater	5	3	60
4	IRGC	Isozyme group 4, Satellite, Deepwater	2	0	0
5	IRGC	Isozyme group 5, Minor group, Basmati	31	0	0
6	IRGC	Isozyme group 6, Major group, Japonica	90	5	6
7	IRGC	Not classifiable in isozyme group	8	0	0
8	IRGC	Not classified	509	5	1
9	INGER	Improved semidwarf cultivars (breeding lines)	404	8	2
10	Plant Breeding	F_1 hybrids	61	1	2
11	IRGC	*Oryza glaberrima*	111	9	8
12	IRGC	Maturity less than 100 d	979	124	13

Screening was conducted more than twice in screening number 1 to 9 and only once in 10 to 12.
[1]Glaszmann (1987)

Table 2. List of germplasm selected from the screenings in Table 1.

No.[1]	Acc. no.[2]	Cultivar	Origin	No.[1]	Acc.no.[2]	Cultivar	Origin
1	6267	ASD1	India	12	29341	Gasmal 497	Bangladesh
1	8228	Tan Cau 9A	Vietnam	12	29379	Pankait 117-2	Bangladesh
1	8231	Gie 57	Vietnam	12	29394	Rata 294	Bangladesh
1	10214	Chiem Chanh	Vietnam	12	29413	Tupa 7-1	Bangladesh
1	10969	Rojofotsy 738	Madagascar	12	29415	Tupa 13-3	Bangladesh
1	32575	Carreon	Philippines	12	31569	Balam	Bangladesh
1	51300	Guan-Yin-Tban	China	12	31577	Goreswar	Bangladesh
2	6144	FR13A	India	12	31582	Jhari	Bangladesh
2	6246	DA28	Bangladesh	12	31587	Kalamanik	Bangladesh
2	9069	JC148	India	12	31608	Murali	Bangladesh
2	9080	JC178	India	12	34703	Kalmi Lota	Bangladesh
2	19379	N22	India	12	34714	Langka Bini	Bangladesh
3	6538	Bamoia 341	Blangladesh	12	34721	Mary Saita	Bangladesh
3	13746	Taothabi	India	12	34722	Mary	Bangladesh
3	26289	Aswina	Bangladesh	12	34723	Mois Kani	Bangladesh
6	1107	Ta Hung Ku	China	12	34734	Sodo	Bangladesh
6	1112	Hei Chiao Chui Li Hsiang Keng	China	12	34735	Sribail	Bangladesh
6	5310	Kibi	Japan	12	34754	Sonalichikan	Bangladesh
6	13375	Jumula 2	Nepal	12	34756	Ulia	Bangladesh
6	32406	Yangkum (Red)	Bhutan	12	36828	Habiganj Boro 4	Bangladesh
8	537	Chiclayo 1	Peru	12	49200	Jogai	Bangladesh
8	3552	Sathra	Pakistan	12	49222	Koimurali	Bangladesh
8	6091	Bentoubala B	Mali	12	58726	Dhol Goria	Bangladesh
8	26289	Aswina	Bangladesh	12	58746	Loha Chur	Bangradesh
8	77041	California Belle R-16	U.S.A.	12	32387	Chumja	Bhutan
9		7901-TR16-1-1	Turkey	12	38622	Ush	Bhutan
9		BR1870-67-1-3	Bangladesh	12	10754	Cateto Branco	Brazil
9		BR736-20-3-1	Bangladesh	12	10756	Dourado Agulha	Brazil
9		IB16	Burundi	12	39032	Guaiba	Brazil

9		IR41996-50-2-1-3	Philippines
9		IR50363-61-1-2-2	Philippines
9		RP1669-1529-4254	India
9		RP1848-213-5-1	India
10		IR62829A/PUSA150-9-3-1R	Philippines
11	103589	*O. glaberrima*	Cameroon
11	103601	*O. glaberrima*	Cameroon
11	102724	*O. glaberrima*	Ivory Coast
11	103556	*O. glaberrima*	Mali
11	103614	*O. glaberrima*	Mali
11	103707	*O. glaberrima*	Mali
11	103760	*O. glaberrima*	Mali
11	103955	*O. glaberrima*	Senegal
11	103959	*O. glaberrima*	Senegal
12	29138	AUS 351	Bangladesh
12	29142	AUS 355	Bangladesh
12	29147	AUS 360	Bangladesh
12	29151	AUS 364	Bangladesh
12	29152	AUS 366	Bangladesh
12	29154	AUS 368	Bangladesh
12	29155	AUS 369	Bangladesh
12	29242	AUS 464	Bangladesh
12	29245	AUS 467	Bangladesh
12	29251	Baranboro 589	Bangladesh
12	29253	Basful 80-2	Bangladesh
12	29258	Basful 714	Bangladesh
12	29269	Boro 6-2	Bangladesh
12	29271	Boro 10-3	Bangladesh
12	29272	Boro 13-2	Bangladesh
12	29273	Boro 15-1	Bangladesh
12	29274	Boro 16-1	Bangladesh
12	29276	Boro 34	Bangladesh
12	29277	Boro 40-1	Bangladesh
12	29278	Boro 40-2	Bangladesh
12	29282	Boro 69-2	Bangladesh
12	29283	Boro 70-2	Bangladesh
12	29284	Boro 74-1	Bangladesh
12	29285	Boro 76-1	Bangladesh
12	29286	Boro 102-3	Bangladesh
12	29290	Boro 135-1	Bangladesh
12	29291	Boro 139-1	Bangladesh
12	29298	Boro 395	Bangladesh
12	29299	Boro 397	Bangladesh
12	29300	Boro 398	Bangladesh
12	29301	Boro 465	Bangladesh
12	29303	Boro 475	Bangladesh
12	29304	Boro 477	Bangladesh
12	29309	Dhaliboro 7-2	Bangladesh
12	29310	Dhaliboro 70-1	Bangladesh
12	29311	Dhaliboro 74-3	Bangladesh
12	29319	Dhaliboro 174	Bangladesh
12	29326	Gasmal 98	Bangladesh
12	29337	Gasmal 419	Bangladesh
12	29338	Gasmal 438	Bangladesh
12	29340	Gasmal 489	Bangladesh
12	4490	Fa-tien-thou	China
12	10344	Look Saap Yat Choo	China
12	10361	Hung Chiao Ju	China
12	10364	Criollo "La Fria"	China
12	32583	Che-Chang 9	China
12	51330	Hung-Huo-Lai	China
12	59565	Gao Shan Hong Gu	China
12	68002	E 4183	China
12	68027	E 6033	China
12	68042	Er Mo Zhan	China
12	68238	Qian Tou Zao	China
12	68242	San Ceng Lou	China
12	68244	Shan He Zhan	China
12	68245	Sheng Li Wang	China
12	68248	Shui Bai Zhan	China
12	68251	Suan Gu Zao	China
12	68257	Tong Zi Bai	China
12	68264	Wu Shi Zao	China
12	68266	Xia Jiang Zao	China
12	68276	Xi Bai Mi	China
12	72655	Da Ke Zi	China
12	72740	Ke Xie	China
12	73901	Bai Mi Dao	China
12	73903	Bai Mi Ma Zhan	China
12	73910	Bai Zhan Zi	China
12	74191	Tie Xu Zao	China
12	5304	Shiro-beniya	Japan
12	9277	Fujisaka 3	Japan
12	10378	Ci 5780-1	Japan
12	33054	Ekrin (A46-4)	Myanmar
12	9541	Furami Marshi	Nepal
12	9542	Jumali	Nepal
12	9576	Jalmani	Nepal
12	9579	Zaneli	Nepal
12	59096	Kundia Ujala	Nepal
12	10646	Bululran Silang	Philippines
12	19394	Bininuwang	Philippines
12	19395	Binulungan	Philippines
12	11948	Patchaiperumal	Sri Lanka
12	11986	Kaluwee	Sri Lanka
12	11999	Heendikwee	Sri Lanka
12	12004	Kahatawee	Sri Lanka
12	31501	Murungawee	Sri Lanka
12	36275	Kalukandala	Sri Lanka
12	10486	Takao 6	Taiwan
12	10527	Nanton 85	Taiwan
12	10547	Lui Chou 25-108-30	Taiwan
12	10211	Giau Dumont	Vietnam
12	10585	Lua Chien (C6583)	Vietnam
12	16968	Canh Nong Lun	Vietnam
12	29718	Ba Ren	Vietnam
12	10329	Basmati 802	Pakistan
12	13387	Fatehpur 3	Pakistan
12	38668	Girba Jowal	Pakistan

[1]Screening number in Table 1.
[2]Accession number of IRGC.

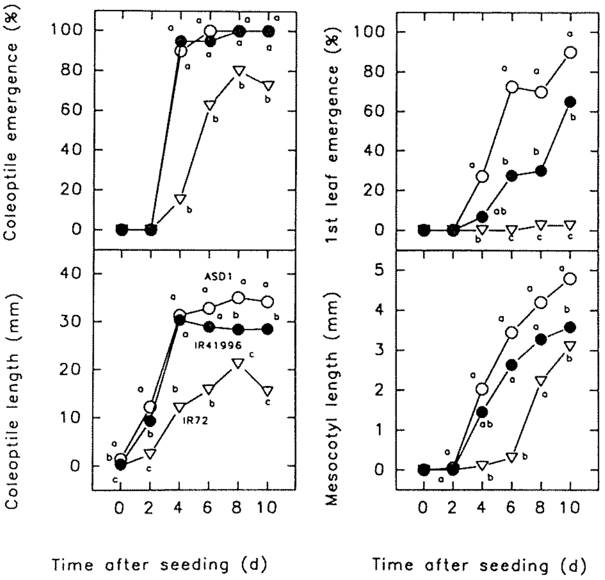

Fig. 1. Seedling establishment of rice cultivars ASD1, IR41996-50-2-1-3 (tolerant to anaerobic conditions), and IR72 (check) in flooded soil[5]. Germinated seeds were sown at 25 mm depth in soil with 25 mm water level in a temperature-controlled (29/21°C day/night) glass room. The emergence of coleoptile and 1st leaf above the soil surface reflects the percentage of numbers of emerged plants to sown plants (10 seeds per pot replicating four). Means having a common letter at each day are not significantly different at the 5% level by Duncan's multiple range test.

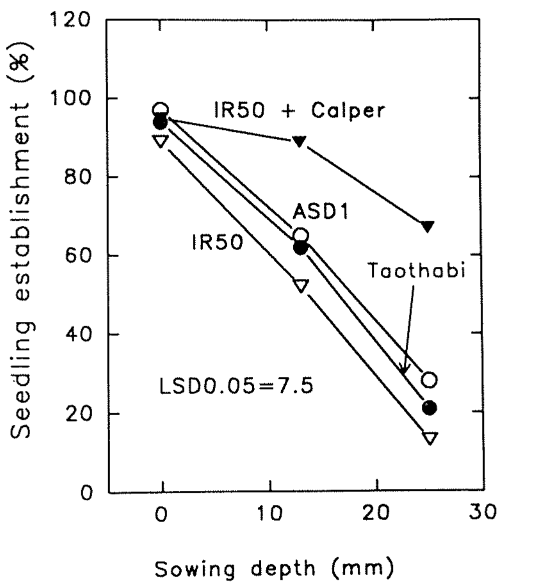

Fig. 2. Effect of sowing depth on seedling establishment of rice cultivars ASD1, Taothabi (tolerant), and IR50 (check), and Calper-coated IR50[28]. The establishment corresponded to the appearance of 1st leaf.

The products of anaerobic decomposition of rice straw inhibited 1st leaf development in flooded soil. The experiment with tolerant and check cultivars indicated that the soil flooded in advance of sowing showed a lower toxicity than the soil flooded at the time of sowing[6], probably due to the decomposition of the toxic substances under flooded conditions[22]. To alleviate damages from toxic substances, flooding the fields in advance of sowing might be necessary for direct seeding. The anaerobic-tolerant cultivars grew better than the check cultivars in spite of the toxicity.

Seed vigor

Seed vigor, the potential for rapid uniform emergence and development of normal seedlings under a wide range of field conditions[4], varies according to the seed age, cultivar, time of harvest, weather during maturation, nutrition, position of seeds on the panicle, specific gravity, mechanical integrity, and presence of pathogens[21]. In the screenings, we often observed that seed source changed the performance of a cultivar.

Treatment to accelerate seed aging during storage significantly reduced the anaerobic seedling establishment (Fig. 3). When seeds were kept for 0-9 d at 100% relative humidity at 43°C, IR36 (check) and JC178 (tolerant) showed a lower percentage of germination and seedling establishment. A tolerant cultivar ASD1, however, did not deteriorate during the aging treatment and maintained a high seedling establishment ability, suggesting that this cultivar is tolerant to seed aging as well. Because the production and postharvest conditions vary among seed sources, seed vigor may differ even among the seed lots of an identical cultivar. Use of a cultivar tolerant to both seed aging and anaerobic conditions might be important to achieve consistent seedling establishment.

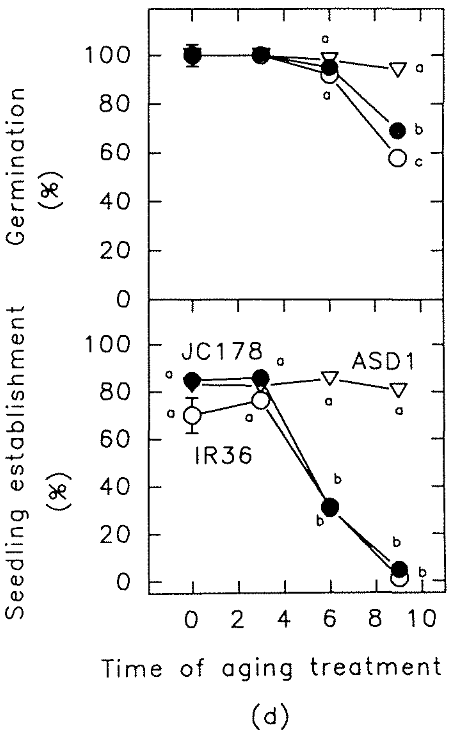

Fig. 3. Effect of time of accelerated aging treatment (100% relative humidity at 43°C) on percentage germination and seedling establishment of rice cutivar ASD1, JC178 (tolerant to anaerobic conditions), and IR36 (check)[23]. To measure the percentage germination, seeds were imbibed in petri dishes lined with wet paper towel at 30°C for 7 d. Seedling establishment was measured in the puddled, drained field by sowing germinated seeds at 10 mm depth during the dry season in 1993. LSD (5%) indicated by the vertical bar is used for the comparison of means between times of aging treatment for each cultivar. Means having a common letter for each aging day are not significantly different at the 5% level by Duncan's multiple range test.

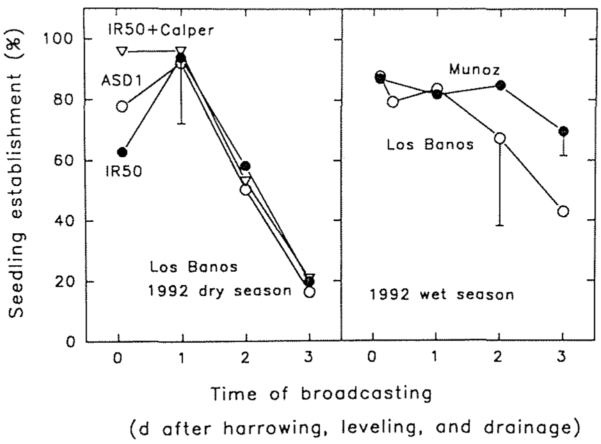

Fig. 4. Effect of time of broadcasting seeds after harrowing, leveling, and draining field on seedling establishment. The vertical bars indicate the LSD 5%. Left: ASD1 (tolerant to anaerobic conditions), IR50 (check), and Calper-coated IR50 were broadcast during the 1992 dry season at Los Baños, Philippines[28]. Right: Six cultivars and one cultivar with Calper coated seeds were broadcast at Los Baños and 12 cultivars, at Muñoz during the 1992 wet season[2]. The points indicate the mean of cultivars and Calper coating.

Sowing method

The methods of placing seeds under the soil surface should be simple so that anaerobic seeding can be practiced by the farmers. The following methods were developed in reference to the established technology for Calper-coated seeds[16].

(1)Anaerobic broadcast seeding. Most farmers broadcast germinated seeds when the soil surface becomes hard (1-2 d after land preparation). In anaerobic broadcast seeding, the seeds are broadcast before the soil surface becomes hard (mostly, on the day of land preparation) so that seeds are under the soil surface.

During the dry season, seedling establishment was optimum when seeds were sown 1 d after land preparation (Fig. 4) mainly because of the seed landing position: half of the seed stays in the soil and the other half remains in the atmosphere. When seeds were sown on the day of land preparation, seeds sank under the soil surface and seedling establishment was reduced, resulting in a clear difference between cultivars and treatments with and without Calper. Sowing at 2-3 d after land preparation reduced seedling establishment due to the poor contact between seed and soil.

During the wet season, sowing at 0-2 d after land preparation resulted in a similar level of seedling establishment, regardless of the cultivars, at the two locations in the Philippines (Fig.4). Because the seeds were splashed by rain, there was little difference in seedling establishment between the seeds sown on the day of land preparation (covered by soil at sowing but exposed to the soil surface by rain-splashing later) and those sown 2 d afer land preparation (seeds stayed on the soil surgace at sowing but were covered by soil by rain-splashing later).

In water seeding, farmers broadcast when the soil particles settle and water becomes clear. Due to the buoyancy, many seedlings are separated from the gound and float. This problem is particularly serious on windy days. Broadcasting seeds on the day of land preparation and covering seeds with a thin layer of soil could be advantageous in preventing the occurrence of floating seedlings. The seeding depth was, however, significantly affected by the timing of sowing after land preparation, soil properties, and intensity of land preparation, resulting in failures of seedling establishment occasionally. In addition, the presence of snails in the standing water destroyed the seedlings. Thus, the technique of water seeding needs to be further developed.

(2)Anaerobic drill seeding. Commercial seeders developed for sowing Calper-coated seeds are useful for anaerobic drill seeding. At IRRI, we modified the IRRI drum seeder (designed for surface drill seeding) to an anaerobic seeder, by attaching buoyant flotation wheels and furrow openers and closers[7]. This seeder can be produced locally for about US$150 per unit. The seeder was successfully operated at Los Baños and Muñoz, Philippines, Yezin and Kyaukse, Myanmar, and Hanoi, Vietnam.

The shortcoming is in dragging the seeder through the puddled soil. This is a problem when the sowing area is large. It is necessary to develop a simple, low-cost seeder that can be pulled by a hand tractor.

Crop establishment and yield potential

Anaerobic drill seeding was tested at Los Baños and Muñoz, Philippines, and anaerobic broadcast seeding at Muñoz, in the 1993 dry season[3]. Percentage of seedling establishment, single seedling weight, height, and biomass

Table 3. Crop establishment and grain yield of anaerobic tolerant and check cultivars planted by anaerobic drill and broadcast seeding at Los Baños and Muñoz, Philippines, 1993 dry season[2,3].

Characters and cultivar group	Los Baños Drill seeding	Muñoz Drill seeding	Muñoz Broadcast seeding
Seedling establishment (%)			
Check	64.0b	24.6b	26.7b
Anaerobic tolerant	80.5a	57.4a	59.1a
Seedling dry weight (mg/plant)			
Check	8.5b	6.8b	7.7b
Anaerobic tolerant	12.8a	8.6a	11.2a
Seedling height (mm)			
Check	91b	70b	76b
Anaerobic tolerant	118a	90a	94a
Seedling biomass (g/m^2)			
Check	1.69b	0.45b	0.49b
Anaerobic tolerant	2.31a	1.34a	1.55a
Grain yield (kg/ha)			
Check	7500a	6270b	6860a
Anaerobic tolerant	7600a	6600a	5810b

Means followed by a common letter in a column under each character are not significantly different at the 5% level by Duncan's multiple range test.

Check cultivars=IR72 and PSBRC4;Anaerobic tolerant cultivars=IR41996-50-2-1-3, IR31802-48-2-2-2, IR50363-61-1-2-2, IR52341-60-1-2-1, BR736-20-3-1, RP1125-3-2-1, 7909-TR16-1-1 (only at Muñoz), BR1870-67-1-3 (only at Muñoz), CO25, and ASD1. CO25 and ASD1 are traditional cultivars, and excluded from yield analysis.

production of anaerobic-tolerant cultivars were significantly greater than those of the semidwarf high-yielding check cultivars (Table 3). The performance of cultivars varied between locations but not between seeding methods. Biomass production was controlled not only by the percentage of seedling establishment but also by single seedling weight. To improve crop establishment, it is first necessary to increase the percentage of seedling establishment, and second to use cultivars with rapid initial seedling growth.

There was little difference in grain yield between anaerobic-tolerant and check cultivars in the two locations when cultivars of improved semidwarf plant type were compared (Table 3). Although tolerance to anaerobic conditions was observed more often in traditional cultivars than in improved semidwarf cultivars (Table 1), a tolerance gene could be incorporated into semidwarf high-yielding plants.

Anaerobic broadcast and drill seeding were successfully tested also in the Mekong Delta[9] and Red River Delta[10] in Vietnam and in Myanmar (Tun Winn et al., unpublished data, 1995), leading to improved crop establishment and higher grain yield compared with check cultivars.

Weed control

The introduction of anaerobic drill seeding makes mechanical and manual weed control possible. This might be useful when a herbicide is not available or its use has to be reduced.

Flooding the field is one of the common weed control practices in ricefields. Anaerobic broadcast seeding with 0-10 cm of water showed that increased water depth not only decreased weed number and weight but also reduced the diversity of weed species (Table 4).

Crop weed competition is the cheapest weed control method[19]. Weed biomasses 56 d after sowing, heading, and maturity were inversely correlated with the characters of seedling establishment, particularly the single seedling dry weight (Table 5). Anaerobic-tolerant cultivars tended to be heavier than the check cultivars, being more competitive against weeds.

The contamination of rice crop fields with noncultivated rice plants (weedy rice) is becoming serious, reducing grain yield and market price. Weedy rice was found to be anaerobic-tolerant[29]. Introduction of anaerobic-tolerant cultivars may reduce the infestation of weedy rice.

Although herbicide application is an essential

Table 4. Effect of water level at the time of seeding on rice seedling establishment, grain yield, and the number of weed species associated with direct-seeded rice plants[18]. The values in parenthesis indicate the relative density of weed species at each water level. Los Baños, 1992 wet season.

Characters of rice and weeds	Water level (cm)					
	0		5		10	
Rice seedling establishment (%)[1]	93a		68a		65a	
Rice grain yield (kg/ha)[1]	2040a		2000a		1660a	
Weed species (number/m^2)						
Sphenoclea zeylanica	768a	(45.2)	79b	(22.5)	57b	(26.1)
Monochoria vaginalis	84a	(4.9)	102a	(29.0)	71a	(30.4)
Cyperus difformis	538a	(31.7)	163a	(46.4)	104a	(43.5)
Echinochloa glabrescens	106a	(6.2)	4b	(1.0)	0b	(0.0)
Ludwigia octovalvis	12a	(0.6)	0b	(0.0)	0b	(0.0)
Fimbristylis miliacea	191a	(11.2)	4b	(1.0)	0b	(0.0)
Total	1698a		351b		230b	

In a row, means followed by a common letter are not significantly different at the 5% level by Duncan's multiple range test.
[1]Mean of rice cultivars tested: ASD1, Farangey, Chin-chan, IR41966-50-2-1-3, BR1870-89-1-1, Caloro/Blue Rose, IR31802-48-2-2-2, CO25 (anaerobic tolerant), IR36, and IR50 (Check) and Calper-coated ASD1 and IR50.

Table 5. Coefficient of simple linear correlation between weed biomass at 56 d after sowing, heading, or maturity and the characters of initial seedling growth in anaerobic broadcast seeding at the water level of 0 cm[18]. Los Blaños, 1992 wet season.

Characters of seedlings 14-17d after sowing	Weed biomass at the growth stage of rice plants		
	56d after sowing	Heading	Maturity
Seedling number/m^2	-0.812**	-0.528	-0.669*
Seedling height	-0.554	-0.556	-0.484
Single seedling dry weight	-0.858**	-0.745**	-0.829**
Shoot biomass/m^2	-0.900**	-0.717**	-0.819**
Leaf area index	-0.788**	-0.647*	-0.745**
Root length	-0.790**	-0.719**	-0.703*
Root biomass	-0.392	-0.420	-0.405

The number of rice seedlings per m^2 at 14 d after sowing ranged from 118 to 241 with mean of 185. The number and species of weeds are described at 0-cm water level in Table 4.
*=significant at the 5% level;**=significant at the 1% level.

component of weed control in broadcast-sown ricefields, it must be reduced as much as possible through the integration of water control, tillage, and seedling establishment method. Intensification of tillage during land preparation, followed by anaerobic broadcast seeding with advanced flooding (3 d rather than the ordinary flooding 7-10 d after seeding), significantly reduced the weed infestation, resulting in higher grain yield than with the ordinary practice even without herbicide application (Table 6),

Lodging

We evaluated the lodging resistance of rice plants by visual observation and by using a push-gauge. A gauge that measures the lodging resistance by pushing a single hill was modified to determine the lodging resistance of a broadcast-sown canopy. The force required for a canopy of 30 cm width to exhibit 45° lodging at 15 cm height was closely correlated with the visual observation (coefficient of simple linear correlation -0.947 significant at the 1% level).

We evaluated the lodging resistance of transplanted, surface broadcast and drill, and anaerobic broadcast and drill seeded rice at two locations in the Philippines (Table 7). The lodging resistance of drill-seeded rice was equivalent to or slightly lower than that of transplanted rice, but significantly higher than that of broadcast-seeded rice. An anaerobic tolerant cultivar IR52341-60-1-2-1 showed greater resistance to lodging at Los Baños than the others.

The analysis of interaction in lodging resistance among planting method, water management, and weed control suggested that weed infestation reduces lodging resistance the most. This was particularly true when we compared the lodging resistance of rice crops grown without herbicide to those grown with herbicide. Anaerobic seeding followed by advanced flooding resulted in a reduction of weed infestation and higher lodging resistance in the plots without herbicide application (Table 6)..

Research needs

The results presented here demonstrate that anaerobic seeding is superior to the current farmers' practice of surface seeding. Because an agricultural technology can not be evaluated from a single perspective, anaerobic seeding should be evaluated further in the integrated system of tillage and water management, and pest control, focusing on resource use efficiency. We need to minimize the costs of tillage, water, herbicides, pesticides, and labor, yet still produce maximum grain yield.

Table 6. Effect of planting method and herbicide application on biomass of weeds, and grain yield and lodging resistance of rice plants[20]. Los Baños, 1994 wet season.

Character and planting method	Herbicide application[6]	No herbicide application[6]	Difference[7]
Weed weight at maturity of rice plants (g/m^2)			
Surface seeding followed by flooding at 10 d[1]	4a	513a	**
Anaerobic seeding followed by flooding at 7 d[2]	17a	340b	**
Anaerobic seeding followed by flooding at 3 d[3]	29a	136c	ns
Rice grain yield (kg/ha)[4]			
Surface seeding followed by flooding at 10 d[1]	5200a	1500c	**
Anaerobic seeding followed by flooding at 7 d[2]	5400a	2800b	**
Anaerobic seeding followed by flooding at 3 d[3]	4800a	4400a	ns
Lodging resistance (kg/0.3 m canopy width)[5]			
Surface seeding followed by flooding at 10 d[1]	0.81a	0.40b	**
Anaerobic seeding followed by flooding at 7 d[2]	0.79a	0.58ab	ns
Anaerobic seeding followed by flooding at 3 d[3]	1.02a	0.77a	ns

[1]The field was plowed once and puddled by harrowing once 7 d after plowing. Seeds were broadcast 1 d after puddling and draining. The field was kept dry until 10 d and then flooded at about 5 cm water depth thereafter. Pretilachlor was applied at 0.3kg ai/ha 1 d after seeding in herbicide-treated plots.

[2]The field was plowed once and puddled three times at 5 d intervals before sowing. Seeds were sown immediately after final puddling and draining. The field was flooded with 5 cm water 7 d after seeding. Pretilachlor was applied at 0.3 kg ai/ha 1 d after seeding in herbicide-treated plots.

[3]Same as above[2] except that flooding was performed 3 d after seeding. Pretilachlor was applied at 0.15 kg ai/ha 3 d after seeding in herbicide-treated plots.

[4]Mean of tested rice cultivars: IR31802-48-2-2-2, IR41996-50-2-1-3, IR50363-61-1-2-2, IR52341-60-1-2-1 (anaerobic tolerant), PSBRC4, PSBRC10(check).

[5]Measured by pushing the 0.3-m width canopy up to 45°at 15 cm height.

[6]In a column under each character, means having the same letter are not significantly different at the 5% level by Duncan's multiple range test.

[7]ns=not significant;*=significant at the 5% level;**=significant at the 1% level.

Table 7. Lodging resistance (kg/0.3 m width of canopy) of 3 rice cultivars planted by 5 methods at Los Baños and Muñoz, Philippines, 1994 wet season (Aragones, Casayuran, Cruz, and Yamauchi, unpublished data). Lodging resistance was measured by pushing a 0.3-m width canopy with a push-gauge at heading at Los Baños and during the ripening stage at Muñoz.

Location and planting method	Cultivar		
	IR41996-50-2-1-3	IR52341-60-1-2-1	PSBRC4
Los Baños			
Anaerobic broadcast seeding	0.40b	0.75b	0.35b
Anaerobic drill seeding	1.10a	1.10a	0.80a
Surface broadcast seeding	0.30b	0.80b	0.40b
Surface drill seeding	0.95a	1.00ab	0.80a
Transplanting	0.90a	0.95ab	0.80a
Muñoz			
Anaerobic broadcast seeding	0.70b	0.65c	0.60c
Anaerobic drill seeding	0.75b	0.90a	0.80ab
Surface broadcast seeding	0.45c	0.70bc	0.70bc
Surface drill seeding	0.80b	0.85ab	0.85ab
Transplanting	1.20a	1.00a	0.95a

In a column under each location, means followed by a common letter are not significantly different at the 5% level by Duncan's multiple range test.

For example, water seeding is a promising technology when we consider only weed control. It is often reported, however, that farmers are using high dosages of insecticides to stablize crop establishment in water-seeded rice in Vietnam. In addition, tungro incidence occurs more frequently in water-seeded than in wet-seeded ricefields[14]. Thus, it is necessary to develop an efficient, environmentally safe, direct seeding technology by integrating a number of technologies.

Acknowledgment

The author would like to thank the collaborators of Philippine Rice Research Institute, National Agricultural Sciences Institute and Cuu Long Delta Rice Research Institute of Vietnam, and Central Agricultural Research Institute of Myanmar for evaluating rice crop performance in connection with the present study.

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熱帯における水稲の湛水土壌中直播技術*

山内　稔

国際稲研究所
フィリピン　ラグナ州ロスバニョス

摘　要

熱帯の水稲直播栽培では，水田を代掻きした２－３日後に催芽種子を土壌表面に散播する。そのため種子は鳥や鼠の害にさらされるのみでなく，強い日差しのため乾燥したり逆に強雨にたたかれ流されたりし，苗立ちは不安定である。また稲の基部は土壌表面にあるため根の地中への張りも弱く，倒状も大きな問題である。さらに直播栽培では稲と雑草の種子がほぼ同時に発芽生育を開始するため雑草害も大きい。そこで遺伝資源の利用と栽培技術の改良により催芽種子を直接嫌気的な堪水土壌中に播種する技術を創出し，苗立ちを安定化させると同時に倒状と雑草害を軽減させた。

堪水土壌中からの苗立ちの優れた適応品種が見い出された。適応品種は東北インドやバングラデシュに起源を持つ天水田稲や深水稲に多く，また多収性の改良品種にも見つかった。適応品種の鞘葉の伸長は嫌気的条件下でも優れており，地表から地中の種子へ効率的に酸素が輸送されていると推定された。

種子の保存状態が悪いと種子が劣化し（Seed aging），苗立ち能力が低下した。品種間に大きなSeed aging耐性の差が認められ，品種ASD1（原産地インド）は嫌気条件下での苗立ちが優れているだけでなくSeed agingに耐性であり，熱帯での直播品種育成の素材になりうる。

代掻き直後の土壌が柔らかい時の散播またはカルパー被覆種子用堪水土壌中直播機の使用により条播で土壌中に播種できた。尚現在日本で使われている直播機は熱帯の開発途上国の農民には高価すぎるため，簡易な直播機を開発した。ここで開発された嫌気土壌中への播種法を英語でAnaerobic seedingと名付けた。

本播種法によりフィリピン，ベトナム，及びミャンマーで安定した苗立ちが得られた。改良された草型の堪水土壌中直播適応品種は移植で得られると同じ程度の多収性を示した。

倒状は散播を条播にすることにより著しく軽減された。また倒状は雑草の生育とも密接に関係していること，適応品種は雑草競合性が高いこと，苗立ちと雑草の発生は水管理と密接に関係していること等が解明され，今後節水栽培の確立を目指した学際的な試験研究が必要である。

キーワード：雑草，種子エイジング，鞘葉，倒状，苗立ち，品種

* 国際稲研究所に対する農林水産省拠出金研究「熱帯における水稲二期作の安定化技術の開発」（平成元年12月～６年11月）の成果の一部。

国際農林水産業研究センター環境資源部（〒305　茨城県つくば市大わし１－２）より派遣。現在：中国農業試験場生産環境部（〒721　広島県福山市西深津町６－12－１）