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Effect of integrated weed management and nitrogen fertilization on the performance of rice under flood-prone lowland conditions

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SUMMARY

Field experiments were conducted at Cuttack, India during 1991–94 to study the effect of tillage, methods of crop establishment and weed control at varying levels of N fertilizer on the performance of rice under flood-prone lowland conditions (0–60 cm water depth). The loss in grain yield of direct-sown rice caused by unchecked weed growth ranged from 18·2 to 59·2% in the different years, and was greater when N fertilizer was applied and when the conventional practice of ploughing the fields just before sowing was followed. Increasing the number of tillage operations before sowing improved the crop stand, reduced weed infestation and, thereby, increased the yield significantly compared with that achieved by conventional tillage. Summer ploughing rather than conventional tillage decreased weed dry weight at harvest by 15·8–53·2% and increased grain yield by 47·4–56·3%. A pre-emergence application of thiobencarb at 2·0 kg/ha, hand weeding once at 20 days of growth and post-establishment inter-crop cultivation at 37–42 days provided effective weed control and increased yield by 32·7–34·7, 36·7 and 28·7–83·9%, respectively. The efficiency of weed control and the resulting increase in rice yield were comparatively greater under puddling than with inter-crop cultivation and herbicide application. The loss in yield due to weeds was negligible when the crop was transplanted due to the incorporation of weeds during puddling and a greater water depth in the later growth stages. Therefore, the grain yield of rice was highest with transplanting followed closely by the direct-sown crop with post-establishment inter-crop cultivation. The response of direct-sown rice to N fertilization up to 60 kg N/ha decreased with fewer ploughings when no weed control measures were adopted. However, the grain yield increased significantly with N application up to 40 kg N/ha when weeds were controlled by cultural or chemical methods. The results suggested that an integrated weed management strategy involving summer ploughing, thiobencarb application and inter-crop cultivation is essential for effective weed control in direct-sown, flood-prone, lowland rice, in order to ensure higher N-use efficiency and crop productivity.

INTRODUCTION

About one-third of the rice crop is grown under rainfed lowland, flood-prone and deepwater ecosystems, mostly in south and south-east Asia and to some extent in Africa (IRRI 1993). In India, the crop occupies nearly 17 million hectares under these conditions (40% of the total area) and such areas are largely concentrated in the eastern parts of the country (FAI 1994/95). The productivity of rice in these ecologically harsh environments has remained almost static (1·0–1·5 t/ha) during the last three decades, whereas the green revolution of the mid-sixties has resulted in a several-fold increase from the favourable irrigated ecosystem. Inadequate crop stands resulting from various biotic and abiotic factors is the major cause for low productivity in the flood-prone lowlands (Pande 1984). Drought in the early stages affects seedling emergence and causes mortality of young plants, while flooding, which may occur at any stage of crop growth, results in reduced tillering and dry matter production (Pande & Reddy 1984). Biotic stresses due to weeds and other pests cause varying degrees of damage to the crop under different situations.

Flood-prone lowland rice is mainly established by direct sowing with the onset of monsoon rains but, in some areas, transplanting is also practised (Sharma

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1995). These areas are monocropped with long-duration photosensitive rice varieties and the fields remain not only fallow but also unploughed during the following dry season. Ploughing starts with the onset of pre-monsoon showers as a preliminary to establishing the next crop. Due to the limited availability of bullocks to prepare the land in the short time available for direct seeding, the sowing is usually done in poorly-prepared fields. This not only results in poor seedling emergence but also in early weed infestation and inefficient utilization by the crop of the basally-applied fertilizers (Moody 1991). Weed infestation is particularly severe in the early stages when the crop grows under an aerobic upland environment. In the later stages, aquatic weeds emerge and grow mostly at or below the water surface, particularly when the crop stand is poor. Weeds are more vigorous competitors and use a greater proportion of the fertilizer applied to the rice crop (Baltazar & De Datta 1992). Fertilization with N at higher rates without adequate weed control has been found to be more harmful than a lower rate of N with good weed control (De Datta & Barker 1977; Hassan & Rao 1993).

Unchecked weed growth causes average yield losses of *c*. 60% in rainfed lowland rice (Moody 1990; Moorthy & Rao 1991), and these are greater in direct-sown than in transplanted crops (Baltazar & De Datta 1992). Various cultural or chemical methods are employed for controlling weeds under different situations. An unusual post-establishment inter-crop cultivation practice, locally known as *beushaning*, is followed predominantly in broadcast-sown lowland rice for controlling weeds in eastern India (Fujisaka *et al*. 1991; Moorthy & Rao 1991). This practice consists of a 'blind' cross-ploughing about a month after sowing, with a country plough (which does not turn the soil) when water has accumulated in the field. This is followed by laddering (levelling) and redistribution of uprooted rice seedlings in the vacant spaces. In spite of being labour intensive, mechanical weeding in the early stages is the most common direct weed control method but the manual removal of the weeds becomes difficult later in the season, due to the greater depth of water in the field. Chemical weed control through the commonly used pre-emergence herbicides (such as butachlor and thiobencarb) has been widely investigated but their efficiency depends on the water regime, soil tilth, composition of the weed flora and environmental conditions (Baltazar & De Datta 1992). Annual grasses, broad-leaved and aquatic weeds are controlled effectively by the above herbicides (Moody *et al*. 1986; Baltazar & De Datta 1992; Sharma & Reddy 1992). However, the perennial species, including sedges, can be controlled by more intensive tillage operations during the dry season after harvesting the rainy season crop (Bhagat *et al*. 1996). Soil puddling ensures good weed control (Reddy & Hukkeri 1983) but the transplanted crop is often exposed to the risk of excess water stress, which might result in poor performance under flood-prone conditions (Reddy & Panda 1988; Sharma 1994). The present studies were undertaken in order to evaluate the effect of tillage, weed control practices and N fertilizer on the performance of direct-sown and transplanted rice under flood-prone lowland conditions.

MATERIALS AND METHODS

Field experiments were conducted at the Central Rice Research Institute, Cuttack, India during the rainy season (May–December) 1991, 1992 and 1994. The soil of the experimental site was an alluvial sandy clay loam of the Mahanadi delta with pH 6·8; organic C, 0·83%; total N, 0·09%; available P, 22 kg/ha; and available K, 128 kg/ha. Four experiments were done: one in 1991, two in 1992 and one in 1994. In Expt 1, the effect of varying tillage involving the ploughing of fields after the harvest of the previous rainy season rice crop (mid-January), ploughing in summer (mid-March) and just before sowing (end of May) (conventional tillage) was studied on direct-sown rice along with different rates of N fertilizer. In Expt 2, weed control practices along with varying N rates were tested on the direct-sown crop under conventional tillage. In Expt 3, the effect of summer ploughing and conventional tillage was studied on direct-sown *beushaned* and puddle-transplanted crops along with N fertilizer rates. Experiment 4 investigated the effect of tillage along with different weed control practices and N rates. Details of the treatments in the different experiments are given in Table 1.

Ploughing was done with a tractor-drawn cultivator, criss-crossed each time, to a depth of 15–20 cm. Conventional tillage involved the usual practice of ploughing the fields at the onset of pre-monsoon showers at the end of May for the direct-sown crop and for the transplanted crop after the accumulation of water in the field following the outbreak of the monsoons in July. Direct seeding was done in plough furrows (3–5 cm deep) spaced at 20 cm using 400 seeds/m^2 (80 kg/ha), whereas transplanting was done at a spacing of 20×15 cm, using 3–4 seedlings/hill, which had been raised elsewhere in nursery seed-beds. The herbicide thiobencarb was sprayed at 2·0 kg/ha in 500 litres of water within a week of sowing in moist soil. Hand weeding involved the manual uprooting and removal of weeds at 20 days after seedling emergence. *Beushaning* was done after the accumulation of water in the field at 37 and 42 days of growth in 1992 and 1994 respectively. Puddling of soil was done thoroughly at the same time as *beushaning* and nursery seedlings of the same age as the direct-sown crop were transplanted.

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Table 1. *Experimental factors and treatment combinations involving tillage, weed control practices and N fertilizer rates applied to rice in different experiments at Cuttack, India*

	Expt 1 (1991)	Expt 2 (1992)	Expt 3 (1992)	Expt 4 (1994)
Experimental factor				
Tillage (A)	(i) One ploughing in May (conventional) (ii) Two ploughings in Mar and May (iii) Three ploughings in Jan, Mar and May	Conventional tillage	(i) Conventional tillage (ii) Summer ploughing	(i) Conventional tillage (i)) Summer ploughing
Weed control practices (B)	No weeding	(i) No weeding (ii) Hand weeding (iii) Chemical weeding (iv) *Beushaning*	(i) No weeding (ii) *Beushaning* (iii) Puddling (Transplanted)	(i) No weeding (ii) Chemical weeding (iii) *Beushaning* (iv) Puddling (Transplanted)
N application rates (C)	(i) No nitrogen (ii) 20 kg N/ha (iii) 40 kg N/ha (iv) 60 kg N/ha	(i) No nitrogen (ii) 20 kg N/ha (iii) 40 kg N/ha (iv) 20 kg N (basal)+ 20 kg N/ha (40 DAG)	(i) No nitrogen (ii) 40 kg N/ha	(i) No nitrogen (ii) 40 kg N/ha
Treatment combination	A × C ($3 \times 4 = 12$)	B × C ($4 \times 4 = 16$)	A × B × C ($2 \times 3 \times 2 = 12$)	A × B × C ($2 \times 4 \times 2 = 16$)
Experimental design	Split-plot A, Main plot C, Subplot	Split-plot B, Main plot C, Subplot	Split-plot A, Main plot B × C, Subplot	Split-plot A, Main plot B × C, Subplot
Replications	3	3	3	3
Plot size	5×3 m²	$4{\cdot}6 \times 2{\cdot}6$ m²	$4{\cdot}6 \times 2{\cdot}6$ m²	5×3 m²

A semi-dwarf, long-duration, photosensitive rice cultivar, 'Gayatri', was used in all the experiments.

A common basal dose of 8·7 kg P/ha as single superphosphate and 16·7 kg K/ha as muriate of potash was applied in all the experiments. Basal N was applied as prilled urea in the plough furrow as per treatment in the direct-sown crop. However, urea supergranules were placed in the transplanted crop and also in direct-sown crop where top-dressing of N was done. Observations were recorded on daily variations in flooding patterns and on the growth of rice and weeds. At maturity, weed dry weight, yield attributes and straw yield of rice were recorded from 1 m² sample areas in two different places and grain yield was recorded after discarding the border rows from each plot. The data were submitted to analysis of variance and the treatment differences were compared at the 5% level of significance.

RESULTS

Weed flora

The following weeds were observed in the field: broad-leaved – tropical spiderwort (*Commelina benghalensis*), joy weed (*Alternanthera sessilis*), mundri (*Ludwigia perennis*) and joint-vetch (*Aeschynomene indica*); grasses – Siberian or shama millet (*Echinochloa frumentacea*) and spangletop (*Leptochloa chinensis*); sedges – umbrella sedge (*Cyperus iria*) and bulrush (*Scirpus maritimus*); and aquatic weeds – musk grass (*Chara zeylanica*) and eriocaulon (*Eriocaulon sieboldianum*).

Fluctuations in water depth in the field

Germination of rice seeds occurred with the pre-monsoon showers which started after sowing. Water started accumulating in the field from mid-July onwards following the regular outbreak of the monsoon (Fig. 1). In 1991, water accumulated in the field from 22 days after germination (DAG) and increased rapidly up to 32 cm at 26 DAG and a maximum of 54 cm at 58 DAG. In 1992, water accumulated from 32 DAG and increased rapidly up to a peak depth of 51 cm at 46 DAG. Although the water depth at the time of *beushaning* and transplanting at 37 DAG was favourable (*c.* 5 cm), these crops experienced complete submergence for 4–5 days soon afterwards. However, the adverse effect on crop growth was not great because the water depth receded to < 15 cm and remained generally between 15 and 25 cm during the major part of the period of crop growth. In 1994, the water depth fluctuated widely and rose to a greater depth than in the previous years. It rose from 22 DAG up to 54 cm at 36 DAG and

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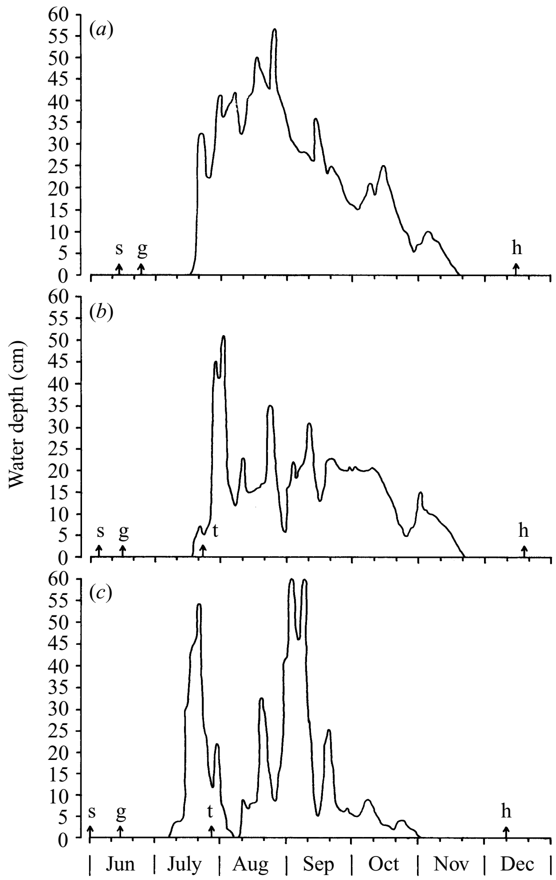

Fig. 1. Variations in water depth (cm) in the field measured daily during the growth period of rice in (*a*) 1991, (*b*) 1992 and (*c*) 1994 at Cuttack, India. Arrows indicate the dates of sowing (s), germination (g), *beushaning*/transplanting (t) and harvesting (h) of rice.

then receded to zero at 52 DAG. The crops *beushaned* or transplanted at 42 DAG at 12 cm water depth established well because the water depth remained at < 10 cm up to 20 days thereafter. Peak flooding of 60 cm occurred in the late vegetative growth stages (78/84 DAG) and the crops experienced extreme excess water stress for 10 days. Water depth showed a declining trend from the end of September onwards and receded completely well before crop maturity during December.

Experiment 1

Increasing tillage operations before sowing decreased weed biomass and thus helped to increase the grain yield of rice significantly ($P < 0{\cdot}05$) (Table 2). With the off-season ploughings, particularly in summer, the weed population was decreased from the early stages. Dry weight of weeds at harvest was lower, whereas plant height and number and weight of panicles of rice were higher with more ploughings, leading to an increased production of grain and straw. The mean effect of N fertilizer rates on plant height, number and weight of panicles and grain yield was not significant.

Interaction between tillage and N application rates revealed that weed dry weight decreased significantly ($P < 0{\cdot}05$) as the number of ploughings was increased, but there was a progressive increase with increasing rates of N application up to 60 kg N/ha (Table 3). On the other hand, the effect of N rates on grain yield varied with the number of ploughings. The yield response to N fertilizer decreased with reduced tillage due to the corresponding increase in weed dry weight. The effect of N application on grain yield of rice was significant ($P < 0{\cdot}05$) up to 20 kg N/ha under three ploughings but there was no response to N under two ploughings. Furthermore, the yield decreased with successive increases in N dose under one ploughing, particularly at the higher rates of 40 and 60 kg N/ha.

Experiment 2

Different weed control practices provided satisfactory weed control and improved the growth and yield attributes of rice significantly ($P < 0{\cdot}05$) compared with no weeding (Table 4). Weed dry weight at harvest under hand weeding and *beushaning* was similar but relatively lower than that under chemical weed control because thiobencarb was not effective against joint-vetch. The grain yields under various weed control treatments were equal but significantly ($P < 0{\cdot}05$) higher than the unweeded control. The application of 40 kg N/ha, either in a single basal dose or in two equal splits at sowing and 40 DAG, resulted in the same yield as with a basal application of 20 kg N/ha.

Interaction between weed control practices and N application rates revealed that N fertilization proved beneficial only when the weeds were controlled either by cultural or chemical methods (Table 5). The grain yield remained unaffected with N application under unweeded conditions but there was a significant ($P < 0{\cdot}05$) increase in yield under different methods of weed control. On the other hand, weed weight increased significantly ($P < 0{\cdot}05$) with N applications under unweeded control but remained almost unchanged under the hand weeding, chemical weeding and *beushaning* treatments.

Experiment 3

Summer ploughing decreased weed biomass and improved the number and weight of panicles of rice, which led to a comparatively higher grain yield production than with conventional tillage (Table 6). Weed dry weight at harvest was minimal in the puddle-transplanted and direct-sown *beushaned* crops

Table 2. *Mean effect of tillage and N application rates on the performance of rice and dry weight of weeds at harvest under flood-prone lowland conditions at Cuttack, India (Expt 1)*

Treatments	Plant height at maturity (cm)	Panicles/m²	Panicle weight (g)	Grain yield (t/ha)	Straw yield (g/m²)	Weed dry weight (g/m²)
Tillage						
One ploughing in May	120	107	2·59	2·33	650	310
Two ploughings in Mar and May	125	116	3·00	3·08	717	189
Three ploughings in Jan, Mar and May	125	124	3·52	3·44	741	112
S.E. (4 D.F.)	2·8	5·7	0·079	0·117	36·5	8·9
N rates (kg/ha)						
0	120	110	3·11	2·95	587	164
20	125	116	3·04	3·06	725	191
40	124	113	3·01	2·94	734	219
60	124	122	2·98	2·84	765	241
S.E. (18 D.F.)	2·5	4·6	0·071	0·089	25·7	7·7

Table 3. *Interaction between tillage and N application rates on grain yield of rice and dry weight of weeds at harvest under flood-prone lowland conditions at Cuttack, India (Expt 1)*

	N application rates (kg/ha)			
Tillage	0	20	40	60
	Grain yield of rice (t/ha)			
One ploughing in May	2·61	2·52	2·17	2·02
Two ploughings in Mar and May	3·09	3·21	3·03	2·97
Three ploughings in Jan, Mar and May	3·15	3·44	3·63	3·53
	Dry weight of weeds (g/m²)			
One ploughing in May	248	283	332	378
Two ploughings in Mar and May	165	176	202	212
Three ploughings in Jan, Mar and May	79	114	123	132
	Grain yield		Weed dry weight	
S.E. (18 D.F.)	0·154		13·3	

compared with unweeded controls. The mean grain yield was highest with transplanting, which was 2·0 t/ha more than the direct-sown, unweeded crop. *Beushaning* resulted in lower yields than transplanting but these were significantly higher than the *un-beushaned* crop. Nitrogen fertilization also increased the yield, which was associated with a greater number of heavier panicles.

Interaction between tillage and weed control practices revealed that the effect of summer ploughing was observed only on direct-sown unweeded rice when it reduced weed infestation and improved early crop vigour. This resulted in significantly ($P < 0·05$) higher grain yield compared with ploughing just before sowing (Table 7). However, *beushaning* resulted in similar yields, irrespective of tillage, due to the removal of weeds at a relatively early crop growth stage. On the other hand, the performance of transplanted crops tended to be better in plots puddled just before transplanting than in plots ploughed during the summer. Furthermore, fertilization with N did not prove to be beneficial to the direct-sown, unweeded crop due to an increase in weed dry weight. However, increases in yield of puddle-transplanted and direct-sown *beushaned* crops with 40 kg N/ha were significant ($P < 0·05$) compared with no N application.

Experiment 4

The rice yield in this experiment was low due to an inadequate crop stand following prolonged flooding at both the early and late vegetative stages. This led to greater plant mortality and restricted tiller production, resulting in only 50–70 panicles/m² at maturity. The mean grain yield was significantly ($P < 0·05$) increased by summer ploughing compared with conventional tillage because weed growth was reduced and there was an increase in the number and weight of panicles (Table 6). The rice plants were shorter and produced fewer panicles/m² under unweeded conditions than when weed growth was checked. Controlling weeds by cultural or chemical methods improved the grain yield significantly ($P < 0·05$). The highest yield was achieved by transplanting, where the yield of grain was equal to that from the direct-sown *beushaned* crop and significantly more than that achieved by chemical weeding. Increase in yield was associated with decrease in weed dry weight, which was lowest under transplanting. The use of thiobencarb did not

Table 4. *Mean effect of weed control practices and N application rates on the performance of rice and dry weight of weeds at harvest under flood-prone lowland conditions at Cuttack, India (Expt 2)*

Treatments	Plant height at maturity (cm)	Panicles/m²	Panicle weight (g)	Grain yield (t/ha)	Straw yield (g/m²)	Weed dry weight (g/m²)
Weed control practices						
No weeding	104	159	1·84	2·75	727	227
Hand weeding	118	256	2·11	3·76	928	15
Chemical weeding	112	217	2·17	3·65	943	44
Beushaning	109	182	2·57	3·54	718	23
S.E. (6 D.F.)	2·2	8·2	0·044	0·078	38·3	6·4
N rates (kg/ha)						
0	100	186	2·07	3·07	666	64
20	112	206	2·12	3·43	804	79
40	114	213	2·22	3·56	892	87
20+20	117	209	2·28	3·63	954	79
S.E. (24 D.F.)	1·4	5·3	0·025	0·062	33·5	5·1

Table 5. *Interaction between weed control practices and N application rates on the grain yield of rice and dry weight of weeds at harvest under flood-prone lowland conditions at Cuttack, India (Expt 2)*

N rates (kg/ha)	Weed control practices: No weeding	Hand weeding	Chemical weeding	*Beushaning*
	Grain yield of rice (t/ha)			
0	2·63	3·32	3·23	3·10
20	2·87	3·68	3·67	3·50
40	2·83	3·97	3·73	3·72
20+20	2·67	4·07	3·95	3·83
	Dry weight of weeds (g/m²)			
0	181	15	48	11
20	218	14	54	29
40	280	13	35	20
20+20	229	17	38	32
	Grain yield		Weed dry weight	
S.E. (24 D.F.)	0·124		10·2	

control joint-vetch effectively and there were also some late-emerging aquatic weeds, which reduced its effectiveness. Application of 40 kg N/ha increased plant height and number and weight of panicles, resulting in a significantly ($P < 0·05$) higher grain yield than where no N was given, despite the fact that there was some increase in weed dry weight.

Interactions between weed control practices and tillage or N application rates had significant effects on the grain yield of rice (Table 7). Inadequate land preparation under conventional tillage resulted in a profuse growth of weeds from the early stages, which resulted in a greater reduction in yield under unweeded treatments and chemical weeding compared with *beushaning* and puddling. The difference in yield between summer ploughing and conventional tillage was reduced under *beushaning* and puddling due to a reduction in weed growth. Basal fertilization with N increased weed biomass and proved to be of no benefit to the unweeded crop. However, there was a significant ($P < 0·05$) increase in yield following the application of N when weed growth was reduced by either cultural or chemical methods.

DISCUSSION

The present experiments examined the effects of tillage, method of stand establishment, weed control and N fertilizer application on the growth and yield performance of flood-prone lowland rice. An understanding of the interactions among the different experimental factors is important in order to evolve an appropriate integrated weed management strategy. The results revealed that the yield of rice varied in the different years due to variations in flooding patterns and with the experimental factors which affected weed growth. The average loss in grain yield of direct-sown rice caused by unchecked weed growth compared with the best weed control practice ranged from 18·2 to 59·2%, and was comparatively greater with the application of N fertilizer than without N and under conventional tillage than summer ploughing (Table 8). It is evident from Fig. 2 that, as the dry weight of weeds increased, the grain yield of rice decreased linearly. Regression analysis indicated that the grain yield decreased by 0·42–0·97 t/ha for an increase of 100 g/m² in weed dry weight in the different experiments. The decrease in yield was similar in Expts 1 and 4 as indicated by the near parallel regression lines but was greater in Expt 3 than in Expt 2. This indicates that the yield of rice increased when the weed growth was checked and was proportional to

Table 6. *Mean effect of tillage, weed control practices and N application rates on the performance of rice and dry weight of weeds at harvest under flood-prone lowland conditions at Cuttack, India (Expts 3 and 4)*

	Plant height at maturity (cm)		Panicles/m²		Panicle weight (g)		Grain yield (t/ha)		Straw yield (g/m²)		Weed dry weight (g/m²)	
Treatments	Expt 3	Expt 4	Expt 3	Expt 4	Expt 3	Expt 4	Expt 3	Expt 4	Expt 3	Expt 4	Expt 3	Expt 4
Tillage												
Conventional tillage	108	116	129	58	2·34	2·57	3·04	1·98	524	286	103	142
Summer ploughing	109	115	154	67	2·55	2·79	3·25	2·78	557	312	92	67
S.E. (2 D.F.)	1·5	1·2	4·4	2·4	0·040	0·049	0·076	0·055	20·4	8·5	6·0	3·9
Weed control practices												
No weeding	106	113	100	52	1·67	2·47	1·93	1·73	380	233	221	235
Chemical weeding	—	120	—	64	—	2·74	—	2·33	—	303	—	105
Beushaning	110	114	175	62	2·65	2·73	3·55	2·68	593	314	45	43
Puddling	110	115	150	72	3·00	2·78	3·95	2·77	649	348	24	35
S.E. (20 D.F.)	1·6		3·7		0·035		0·078		17·2		8·1	
(28 D.F.)		1·3		2·5		0·046		0·062		9·5		3·5
N rates (kg/ha)												
0	107	110	139	55	2·31	2·56	3·01	2·12	441	241	83	93
40	111	121	144	70	2·58	2·81	3·28	2·63	640	358	111	116
S.E. (20 D.F.)	1·3		3·0		0·029		0·064		14·1		6·6	
(28 D.F.)		0·9		1·8		0·033		0·044		6·7		2·4

Table 7. *Interaction between weed control practices and tillage and N application rates on the grain yield of rice (t/ha) under flood-prone lowland conditions at Cuttack, India (Expts 3 and 4)*

	Weed control practices			
Treatments	No weeding	Chemical weeding	*Beushaning*	Puddling
Expt 3				
Tillage				
Conventional tillage	1·56	—	3·54	4·02
Summer ploughing	2·30	—	3·57	3·88
N rates (kg/ha)				
0	1·94	—	3·33	3·78
40	1·93	—	3·78	4·12
S.E. (20 D.F.)	0·110			
Expt 4				
Tillage				
Conventional tillage	1·35	1·80	2·34	2·42
Summer ploughing	2·11	2·86	3·02	3·13
N rates (kg/ha)				
0	1·55	2·02	2·43	2·50
40	1·91	2·64	2·94	3·05
S.E. (28 D.F.)	0·126			

the decrease in weed dry weight at harvest. Based on mean data, the average increase in yield was 0·5 t/ha for a decrease of 100 g/m² in weed dry weight.

Tillage before sowing resulted in fine soil tilth and good seed-bed preparation, which facilitated deeper sowing and placement of fertilizers at a required depth in the soil. Seedling emergence and initial growth of the rice plants was better, and weed population and growth were lower under summer ploughing than with conventional tillage treatments.

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Table 8. *Average loss in grain yield (%) of direct-sown rice caused by unchecked weed growth under flood-prone lowland conditions at Cuttack, India*

Tillage	Expt 2		Expt 3		Expt 4	
	No N	40 kg N/ha	No N	40 kg N/ha	No N	40 kg N/ha
Conventional tillage	18·2	25·7	52·2	59·2	38·5	45·6
Summer ploughing	—	—	31·2	38·9	34·3	36·8

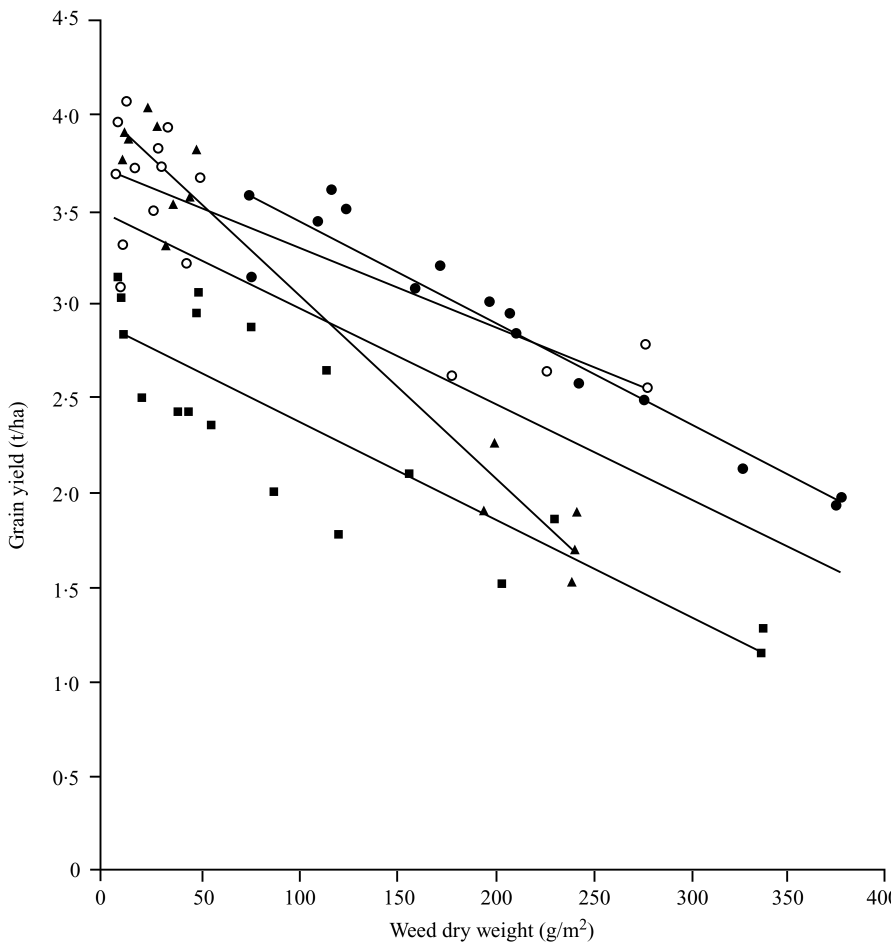

Fig. 2. Relationship between grain yield of rice (Y, t/ha) and dry weight of weeds at harvest (X, g/m²) in four different experiments.
Expt 1 (●); $Y = 4{\cdot}023 - 0{\cdot}00527\ X$, $r = -0{\cdot}937$ ($n = 12$), Expt 2 (○); $Y = 3{\cdot}744 - 0{\cdot}00417\ X$, $r = -0{\cdot}801$ ($n = 16$)
Expt 3 (▲); $Y = 4{\cdot}077 - 0{\cdot}00968\ X$, $r = -0{\cdot}969$ ($n = 12$), Expt 4 (■); $Y = 2.900 - 0{\cdot}00499\ X$, $r = -0{\cdot}823$ ($n = 16$)
Mean (—); $Y = 3{\cdot}540 - 0{\cdot}00499\ X$, $r = -0{\cdot}686$ ($n = 56$)

Similar observations were made by Bhagat *et al.* (1996). The root stubble and seeds, rhizomes or tubers of the previously-growing weeds were uprooted and exposed to hot sun during the summer ploughing, which not only resulted in reduced weed infestation in the early stages but also delayed their emergence in the later stages. The mean weed control efficiency (WCE) in direct-sown crops due to summer ploughing

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Table 9. *Mean increase in grain yield of rice and weed control efficiency over unweeded control (direct-sown crop) as affected by different treatments under flood-prone lowland conditions at Cuttack, India*

	Increase in grain yield (%)			Weed control efficiency (%)		
Treatment	Expt 2	Expt 3	Expt 4	Expt 2	Expt 3	Expt 4
Summer ploughing*	—	47·4	56·3	—	15·8	53·2
Hand weeding	36·7	—	—	93·3	—	—
Chemical weeding	32·7	—	34·7	80·6	—	55·3
Beushaning	28·7	83·9	54·9	89·9	79·6	81·7
Puddling	—	104·7	60·1	—	89·1	85·1

* Compared with conventional tillage.

ranged from 15·8 to 53·2%, which led to an increase in the grain yield of rice by 47·4–56·3% compared with conventional tillage (Table 9). The more thorough the land preparation, the fewer the weeds and the higher the grain yield.

A pre-emergence application of thiobencarb effectively controlled weeds early in the experiments. The herbicide spray was relatively more effective in the summer-ploughed plots because it allowed a uniform coverage of the soil particles and thus ensured almost weed-free conditions for the first 2–3 weeks of crop growth. However, late flushes of some weed species, particularly joint-vetch and spiderwort, caused competition with rice plants and resulted in a low WCE compared with hand weeding and *beushaning* (Table 9). Tillage is known to enhance herbicide effectiveness but neither tillage nor herbicide application alone will provide total control of a diverse and persistent weed community (Bhagat *et al*. 1996). In such situations, it is considered essential to undertake light hand weeding at about a month after sowing for effective season-long weed control.

Mechanical weeding either through hand weeding or *beushaning* controlled early flushes of weed growth effectively which, followed by increasing water depth in the field and rapid canopy closure, prevented the weeds from emerging. Water depth in the field at and immediately after *beushaning* or transplanting has been considered to be the most critical factor in determining good crop establishment, tiller production and the ultimate yield performance of flood-prone lowland rice (Reddy *et al*. 1987; Sharma 1994). *Beushaning* has been found to be harmful when the water depth after the operation remained high ($>$ 30 cm) for prolonged periods ($>$ 1 week), due to a decrease in plant population and adverse effects on tiller production (Sharma 1992). The transplanted crop also performed poorly under such excess water conditions (Reddy & Panda 1988; Sharma 1994). In the present study, both these treatments resulted in very good control of weeds and produced yields better than chemical weeding or the unweeded control (Tables 5 and 6). In Expt 3, although the crops remained completely submerged for 4–5 days soon after *beushaning* or transplanting, the relatively lower water depth (15–25 cm) in the later stages enabled good recovery and establishment. Beneficial effects of *beushaning* on crop performance are due to increased tillering and more profuse growth of plants, owing to the thinning of rice plants, increased tillering, removal of weeds, pruning of roots, and aeration and loosening of the soil in the rhizosphere (Fujisaka *et al*. 1991; Moorthy & Rao 1991).

Soil puddling is a common practice in lowland rice cultivation because it helps to control weeds (Reddy & Hukkeri 1983). In the present study, the transplanted crops remained almost weed-free throughout and produced the highest grain yield (Table 7). The previously-growing weeds were incorporated thoroughly during puddling, and were subsequently discouraged by increased water depth and fast canopy closure. However, some aquatic weeds emerged in the later crop growth stages, although these remained below the water surface and did not appear to affect plant growth adversely. Weed control efficiency and increase in grain yield was comparatively more in the puddle-transplanted than in direct-sown *beushaned* crop, particularly in Expt 3 (Table 9). In this experiment, the relatively better performance of the transplanted crop in plots puddled just before transplanting than in plots ploughed in summer was probably due to the incorporation of organic matter through the stubble and weeds growing in the field during puddling, which might have contributed towards the nutrition of the rice plants. Weeds incorporated through puddling decompose by anaerobic reaction to form ammonium compounds which are retained in the soil and used by the crop (Bhagat *et al*. 1996). Therefore, puddling not only destroys the weeds but allows them to be converted into a useful fertilizer.

The response of rice to N fertilizer decreased under reduced tillage, particularly when no weed control measures were adopted. In other words, N fertilization did not prove to be beneficial under unweeded conditions; rather, the loss in grain yield due to unchecked weed growth increased with N application compared with no N, both under summer ploughing and conventional tillage treatments (Table 8). This was due to the fact that basally-applied N encouraged the vigorous growth of weeds in the early stages which, in turn, suppressed the growth of rice plants (Hassan & Rao 1993). Increased N fertilization was accompanied by a progressive increase in weed dry weight and a consequent reduction in grain yield. This confirmed that weed control was more important under high than under low fertility conditions (De Datta & Barker 1977). Therefore, weeds should be controlled effectively in the initial stages in order to ensure a greater availability of basally applied N fertilizer to the rice.

The results of these studies suggest that tillage before sowing, particularly in summer, is essential for ensuring a good initial crop stand, early weed control and efficient utilization of N fertilizer, leading to the higher productivity of direct-sown lowland rice compared with the conventional practice of ploughing fields just before sowing. However, herbicide application as a pre-emergence spray or *beushaning* is also required for effective season-long weed control. Under the present conditions, where the water depth in the field remained favourable for crop establishment and tiller production, transplanting in the thoroughly-puddled soil is found to be better than direct sowing for controlling weeds and improving productivity. Therefore, adequate weed control through an integrated weed management approach is essential in achieving the efficient utilization of basally-applied N fertilizer by rice plants under flood-prone, lowland conditions.

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