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FERTILIZER TRANSFER TO FLOODWATER DURING DEEP PLACEMENT

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ABSTRACT

This study indicates that presence of water during fertilizer placement plays a major role in reducing fertilizer use efficiency in flooded rice fields. Fertilizer applicators that have been developed in the past have transferred 40 to 70% of the fertilizer to the floodwater during the placement operation. Five possible ways of nitrogen transfer to floodwater are suggested. It was found that up to 40% of the placed fertilizer transfers to floodwater through dissolution during transit from the water surface to the furrow bottom. That was the major avenue for fertilizer transfer. The second major transfer is when the fertilizer solution and/or granules are pushed from the furrow bottom into the floodwater as the furrow closes. Transfers due to nitrogen diffusion through soil or through poorly closed furrows are not high. The authors argue that minimizing nitrogen transfer to floodwater during fertilizer placement is the key to improving fertilizer use efficiency in flooded rice fields. A deep placement applicator concept for minimum transfer to floodwater is proposed. The paper concludes that fertilizer dissolution and the dynamics of fertilizer solution in flooded rice fields have not been fully understood and need further research to improve fertilizer use efficiency.

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FERTILIZER TRANSFER TO FLOODWATER DURING DEEP PLACEMENT

Asian farmers have not been able to effectively utilize fertilizer to boost their yields because of excessive nitrogen (N) losses in wetland paddy cultivation. As early as 1941 in Japan, Shioiri explained how surface-applied ammonia was lost in flooded soils and recommended deep placement of ammonium fertilizers. Several field experiments conducted in Japan from 1942 to 1952 indicated deep fertilizer placement increased rough rice yields by an average of 10% (Mitsui 1955). Despite more than 40 years of work, it has been impossible to implement these important findings at the farm level because suitable applicators have not been developed.

The Agricultural Engineering Department at the International Rice Research Institute (IRRI) has worked to develop deep placement applicators for almost a decade, and many interesting and innovative machines have been devised. Most of them can place fertilizer (Fertilizer in this paper refers to urea fertilizer.) 5 cm or deeper and can close the placement furrow. Many IRRI-developed machines have performed well in experiment station trials, but most have not performed consistently at farm locations. This poor field performance has been baffling, and site and soil differences quite often have been given as reasons for erratic performance.

However, the consistent poor field performance of IRRI machines that meet placement depth and furrow closing criteria suggests that we may have overlooked some important factors that determine applicator performance.

Our main emphasis in developing applicators has been the physical interactions of soil and fertilizer, and we have concentrated on placement at proper soil depth and thorough closing of furrows. Fertilizer-water interaction generally has not been recognized as a major factor affecting fertilizer loss, and engineers paid little attention to it in the design of deep placement applicators.

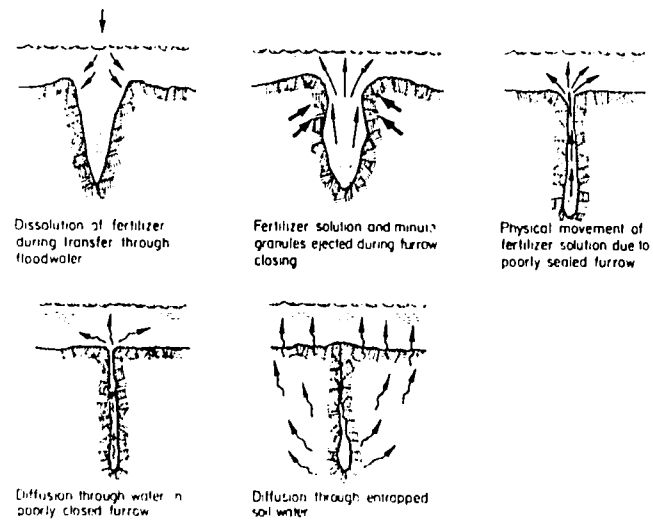
Fertilizer use efficiency on upland farms is 50 to 60% (Craswell and Vlek 1979). On flooded wetland farms, it is 30 to 50% (Prasad and De Datta 1979). In experiments in Pakistan (Ross 1980), dry fertilizer incorporation followed by flooding resulted in 60% applied N recovery by the rice crop, which indicated that flooding after fertilizer application does not reduce fertilizer use efficiency. However, presence of water during placement seems to reduce fertilizer efficiency. A literature review shows no published data on the role of water during placement in decreasing fertilizer use efficiencies in flooded fields.

Because fertilizer volatilization losses are directly affected by floodwater N levels, minimizing floodwater N might be an effective method of reducing fertilizer losses. Isolating the different ways fertilizer moves to floodwater would help to understand the mode and magnitude of such transfer. That, in turn, could help scientists improve applicator designs. A series of laboratory experiments were conducted by the Agricultural Engineering Department to define fertilizer-floodwater interactions.

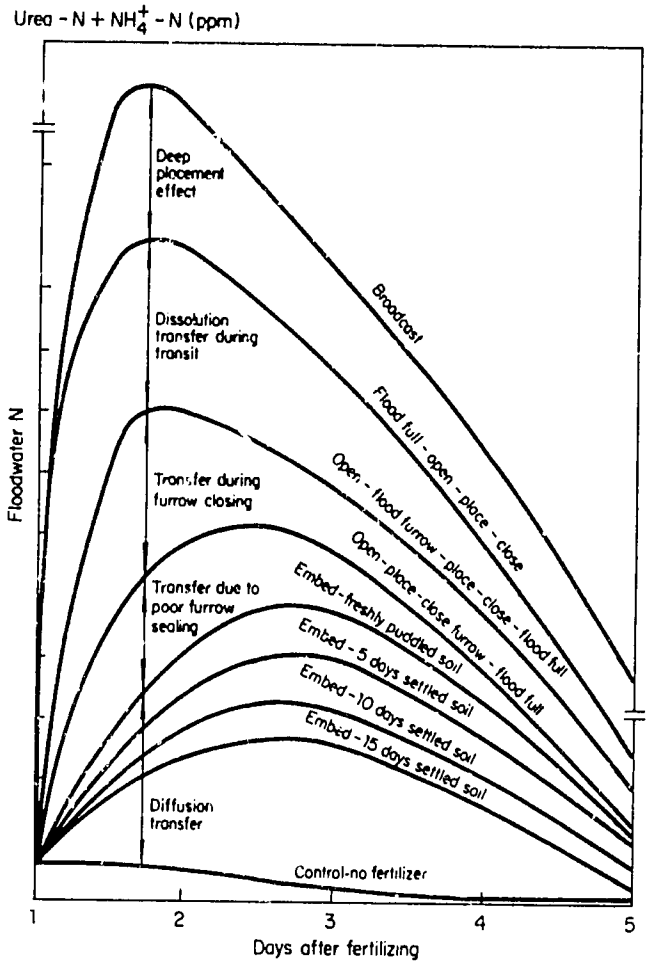
There are five ways by which fertilizer can transfer (Fig. 1) to floodwater during or immediately after placement:

1. through the dissolution of fertilizer as it passes through standing floodwater to the furrow bottom:
2. by upward movement of fertilizer granules or solution caused by the displacement effect when the furrow is closed;
3. by convectional movement of the fertilizer solution through poorly closed furrows;
4. by diffusion through water trapped between poorly closed furrow walls; and
5. by diffusion through water trapped in puddled soil.

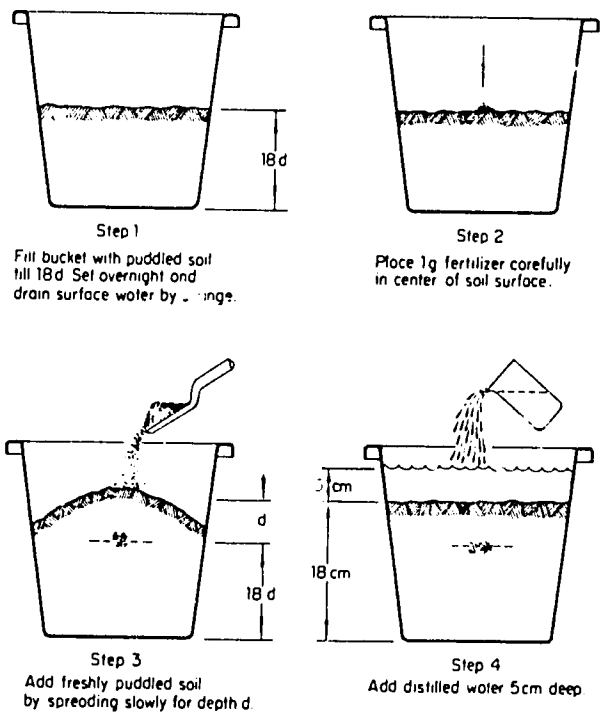
A set of hypothetical curves indicating the various ways of fertilizer transfer to floodwater and the experimental methods to isolate these effects are given in Figure 2.



I. Avenues for fertilizer transfer to floodwater during deep placement.



2. Hypothetical curves showing possible avenues and experimental techniques for evaluating fertilizer transfer to floodwater during placement.



3. Fertilizer embedding experiments (freshly puddled soils). d = embedding depth.

The laboratory experiments were:

1. *Embedding* experiments (Fig. 3) for prilled, forestry-grade, and urea supergranules at 2.5 and 5 cm depths, to study diffusion of fertilizer through freshly puddled soil;
2. *Delayed-fertilizer-release* experiments (Fig. 4) in which embedded prilled, forestry-grade, and supergranule fertilizers were released, without disturbing the soil and after settling periods of 5, 10, and 15 days, to evaluate diffusion rates through settled soils; and
3. *Fertilizer placement* experiments (Fig. 5) with different furrow opening, closing, and flooding sequence, and with varying fertilizer-water contact time of 0, 5, and 10 seconds to understand N transfer rate due to contact with water during placement. (Only prilled fertilizer was used in this experiment because prilled urea is most susceptible to transfer to floodwater during placement and is the only fertilizer commercially available to rice farmers.)

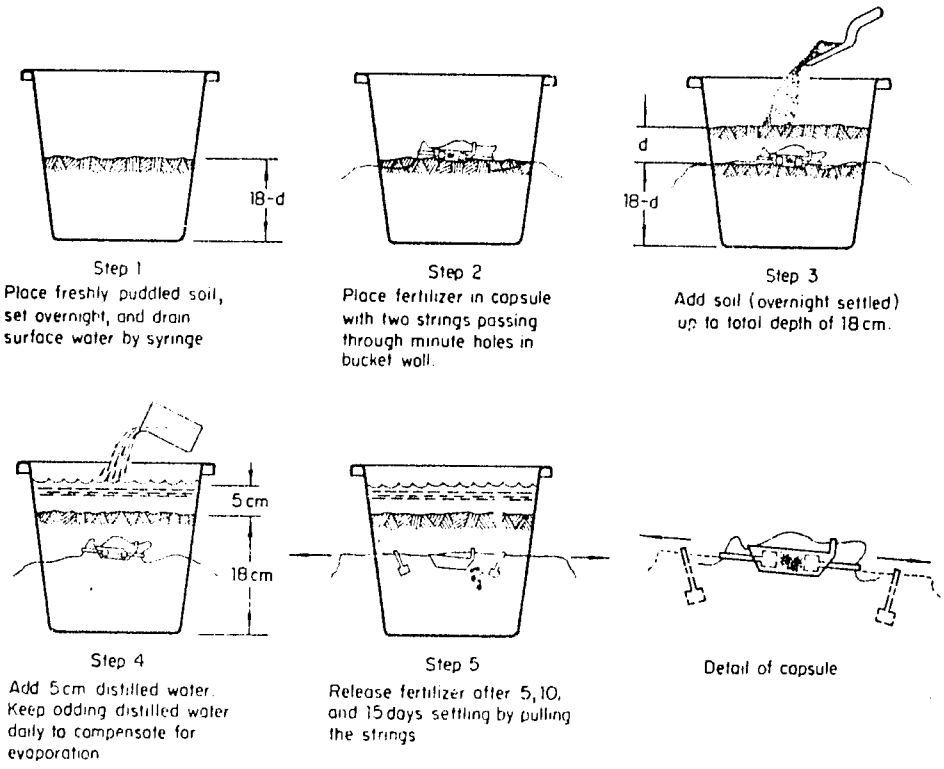
METHODOLOGY

Two preliminary experiments were conducted in 4,000-cc glass beakers: one to study fertilizer embedding and one to evaluate fertilizer-water placement sequence. A fairly high fertilizer rate (232 kg N/ha) was used in the tests. The embedding experiment (Fig. 6) indicated that larger granule size reduces N diffusion to floodwater during the first few days. To a limited extent, deeper placement also lowers N diffusion. The placement sequence experiment (Fig. 7) showed that presence of water during fertilizer placement and speed of furrow closing are important in increasing N diffusion to floodwater. The results of these experiments encouraged us to conduct three replicated experiments to confirm the findings.

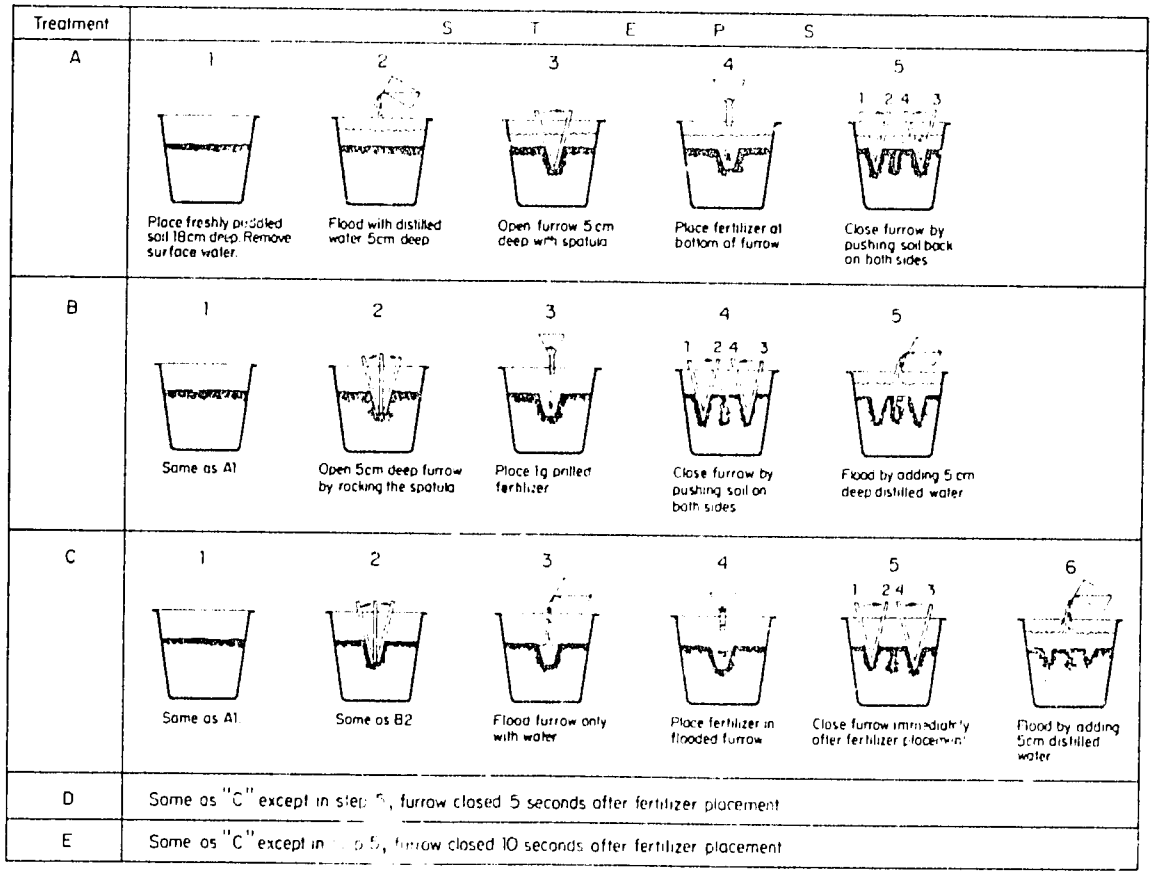
Experiments were conducted in 3-gallon plastic buckets under highly controlled laboratory conditions. Freshly puddled Maahas clay soil from the same fields was used, and 18-cm soil depth and 5-cm floodwater depth were maintained in all experiments. Buckets were kept indoors at about 24°C room temperature. Distilled water was used to avoid chemical contamination.

One gram of fertilizer (equivalent to 94 kg N/ha) was used throughout the tests. Floodwater samples were taken each day for 5 to 7 days after fertilizer placement in freshly puddled soil or after the delayed fertilizer release, and were analyzed for urea and ammonium N concentration.

In the first experiment (Fig. 3), fertilizer diffusion rates in freshly puddled soil for three fertilizer materials and two placement depths were studied. Buckets were filled with freshly puddled soil to 18-*d* cm depth, where *d* was the fertilizer placement depth, and fertilizer was carefully placed at the top of the soil in the center. Additional puddled soil was slowly deposited on top of the fertilizer to obtain the desired embedding depth. Care was taken that the total soil depth after fertilizer embedding was always 18



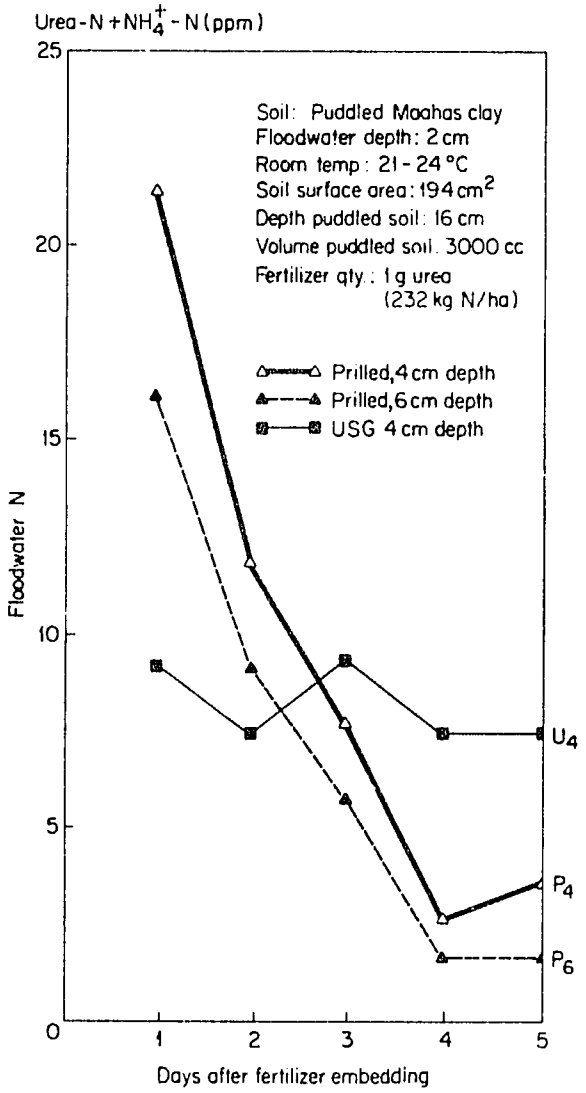
4. Delayed-fertilizer-release embedding experiments (5, 10, 15 days settled soil). d = embedding depth.



5. Fertilizer placement experiments with different placement sequence (freshly puddled soil).

cm. Distilled water was added to obtain the desired 5-cm water depth.

The second experiment (Fig. 4) studied fertilizer diffusion through water entrapped in soil that had settled 5, 10, and 15 days after puddling. A simple device was developed to release fertilizer in settled soil without disturbing the soil. It consisted of the sawed-off cylinder of a disposable plastic syringe that was fitted with two pistons, one on each end. Nylon thread was attached to the pistons so that pulling the ends of the string pulled the two pistons from the cylinder and released the fertilizer. This device with 1-g fertilizer was embedded in the soil, and the string ends



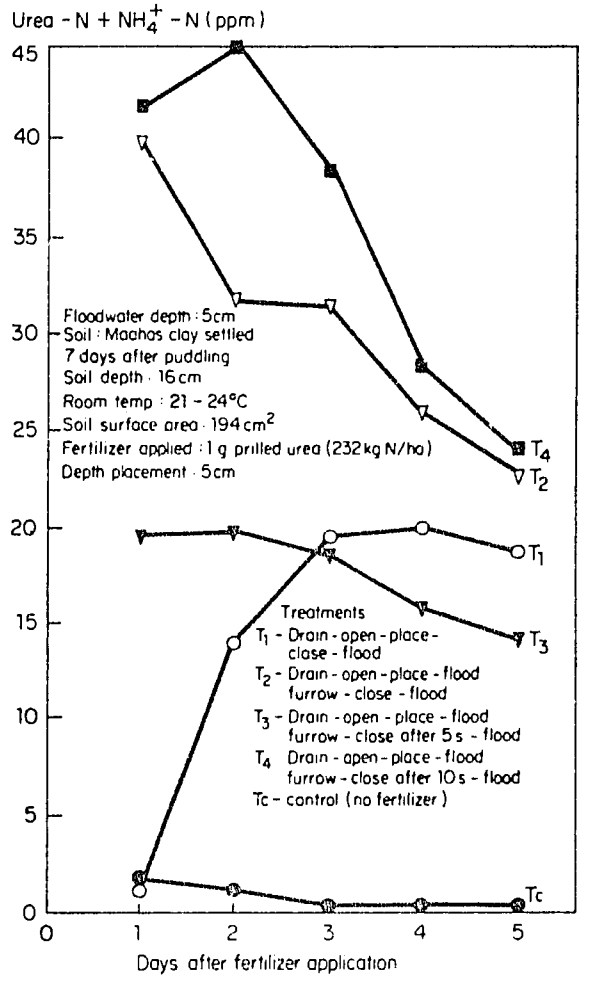
6. Effect of fertilizer embedding depth on urea and ammonium N concentration in floodwater. USG = urea supergranule.

passed through two fine holes pierced on the bucket sidewalls. Fertilizer was released at 5, 10, or 15 days after puddling.

The third experiment (Fig. 5) evaluated the extent of fertilizer dissolution and transfer to floodwater during different fertilizer-water placement sequences. Different combinations of fertilizer placement and water flooding techniques were used to isolate the effect of water during placement (Fig. 5):

1. drain - open furrow - place fertilizer - close furrow - flood to 5 cm;
2. drain - open furrow - place fertilizer - flood furrow and close immediately - flood to 5 cm;
3. drain - open furrow - place fertilizer - flood furrow only - close furrow after 5 s - flood to 5 cm;
4. drain - open furrow - place fertilizer - flood furrow only - close furrow after 10 s - flood to 5 cm; and
5. drain - flood to 5 cm - open furrow - place fertilizer - close furrow.

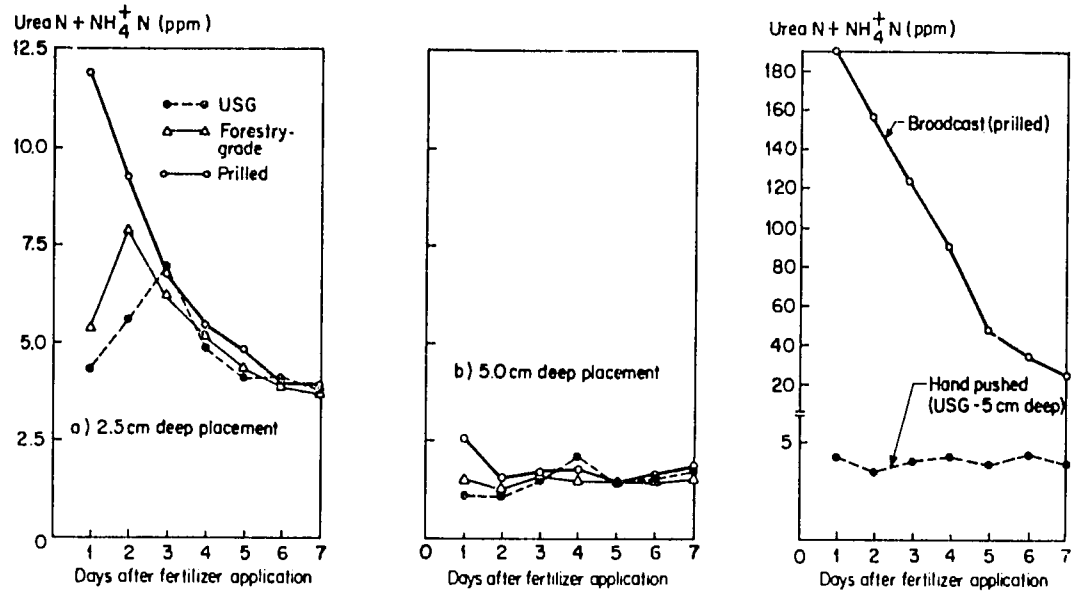
Results of the three experiments are shown in Figures 8 to 14.



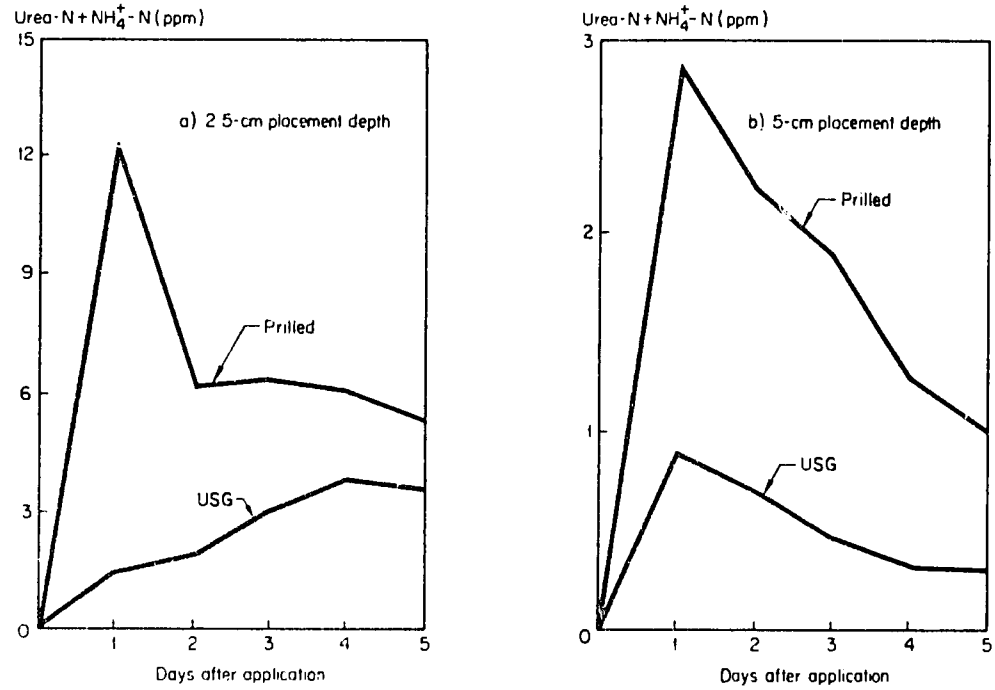
7. Effect of fertilizer placement sequence on urea and ammonium N concentration in floodwater.

MAJOR FINDINGS AND SOME INTERPRETATIONS

1. At 5-cm water depth, N transfer to floodwater increases as fertilizer placement depth increases (Fig. 11). Nitrogen transfer to floodwater can be as high as 43%, 65%, and 76% of broadcast application for 2.5-, 5-, and 7-cm placement depths. The data indicate that conventional fertilizer applicators, which drop fertilizer by gravity into flooded furrows, transfer a large part of the fertilizer into floodwater, and are therefore inefficient for deep placement in flooded fields.
2. Fertilizer dissolution during transit to the furrow bottom at 5-cm depth causes the greatest fertilizer transfer to floodwater (Figs. 13, 14). At 5-cm placement, fertilizer transfer could be as high as 47% of the floodwater N level of broadcast application.
3. Physical movement of the fertilizer solution and fine granules from the furrow bottom to floodwater during furrow closing is the second major source of N transfer to floodwater during deep placement (Figs. 7, 12, 13, 14). With prilled urea, this N transfer at 5 cm placement depth could be as high as 29% of N transfer with surface-broadcast urea.
4. At 2.5-cm placement depth large urea granules showed less diffusion of N to floodwater during the



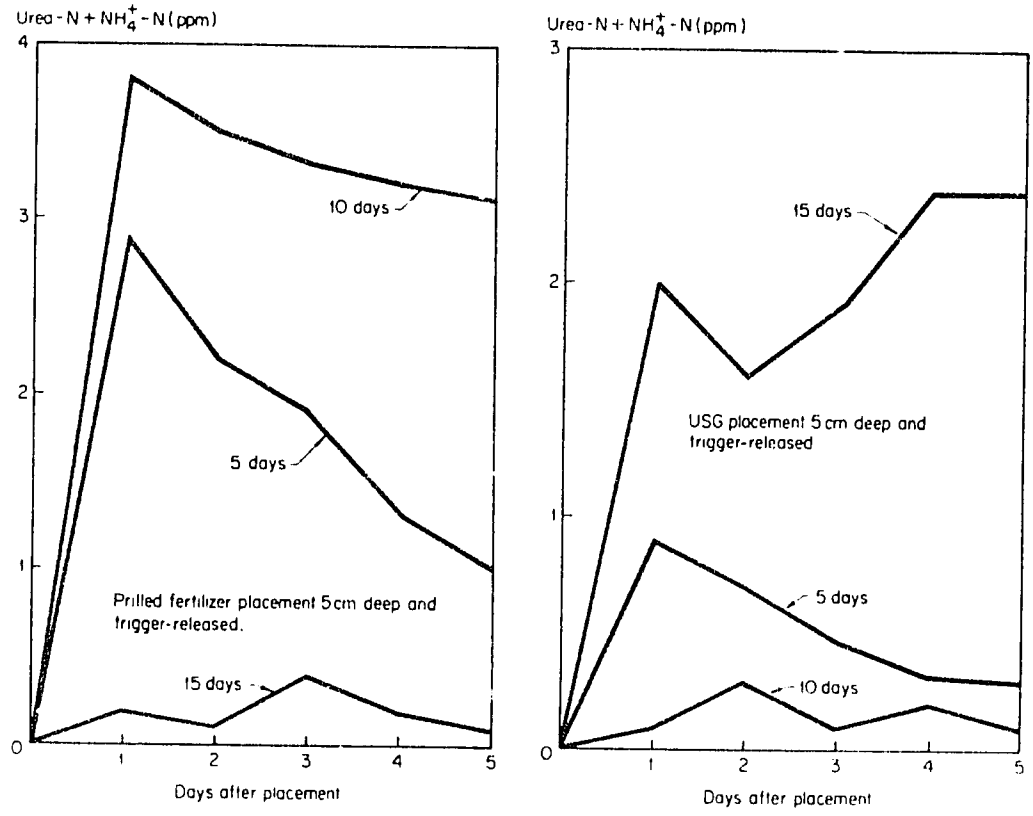
8. Fertilizer embedding experiment on freshly puddled Maahas clay. Floodwater depth, 5 cm; fertilizer rate, 94 kg N/ha. USG = urea supergranule.



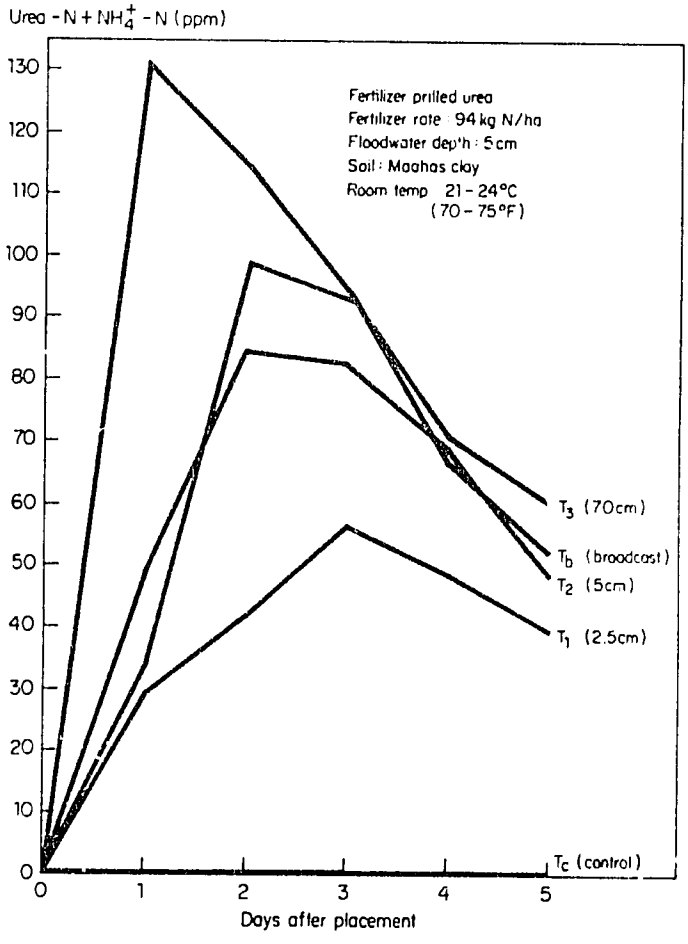
9. Diffusion of N to floodwater through Maahas clay that has settled for 5 days and fertilizer trigger released from 2.5- and 5-cm placement depths. USG = urea supergranule.

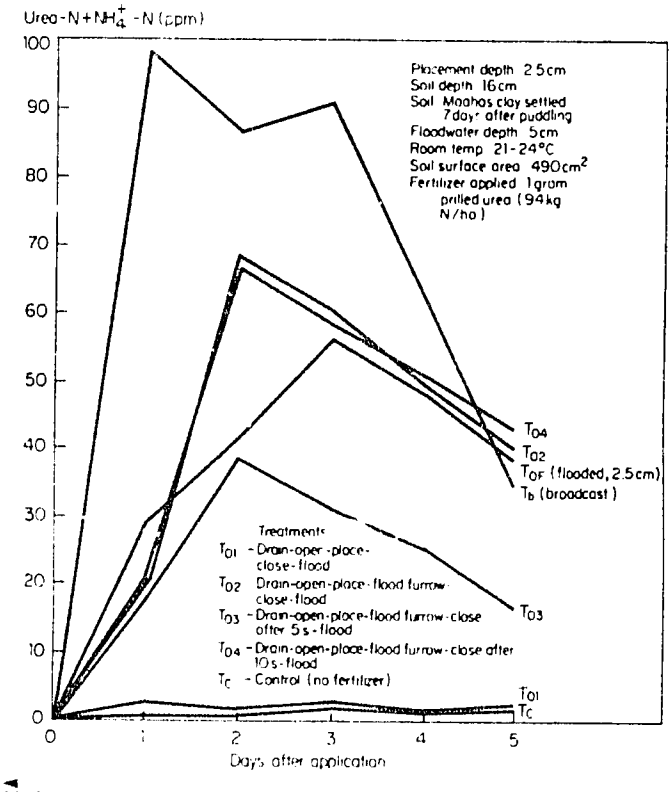
first 2 or 3 days than did prilled or forestry-grade urea. There is little difference in N transfer for the fertilizer materials after 3 days. Deeper embedding of prilled or forestry-grade urea also lowers N transfer (Figs. 6, 8). Finer granule fertilizer must be placed somewhat deeper than larger granules for equal N transfer up to 5 cm. Beyond 5 cm, however, the larger granule size (urea supergranule (USG) or forestry-grade) does not have any advantage over prilled fertilizer, indicating that all urea fertilizer could be placed at the same depth.

5. Quick closing of furrows after placement (+ 0 second) increases N transfer to floodwater as water rushing out of a rapidly closing furrow tends to push some fertilizer granules upward (Figs. 7, 12, 13). Experiments with slower (5 s) furrow closing exhibited lower N transfer than those with more rapid furrow closing. Most applicators developed at IRRI close the furrow quickly, and therefore encourage high N transfer.
6. Transfer through poorly joined furrow walls at 5-cm placement in Maahas clay is about 10% of the N transfer of broadcast application (Figs. 13, 14).
7. Nitrogen transfer to floodwater through diffusion in freshly settled soil after fertilizer has been properly deep placed and covered is not substantial (Figs. 8b, 9, 10).
8. Nitrogen diffusion through soil into floodwater, when prilled fertilizer was embedded at 2.5 cm, was quick and relatively high (Fig. 8a). Maximum N transfer was recorded the first day after placement. With forestry-grade and USG, however, N transfer



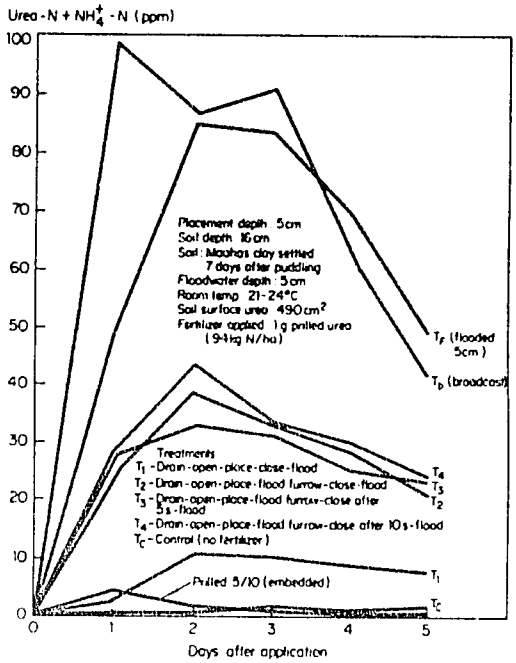
10. Diffusion of N to floodwater through Maahas clay that has settled for 5, 10, and 15 days. USG = urea supergranule.

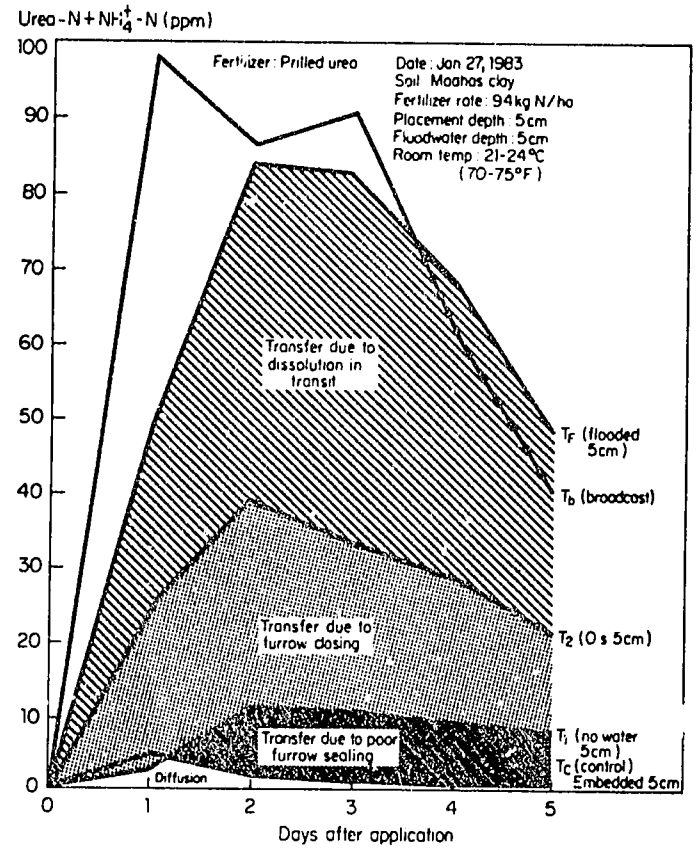




11. Effect of prilled fertilizer placement depth (2.5, 5, and 7 cm) in flooded soils on N transfer to floodwater.

12. Effect of placement sequence with prilled urea at 2.5 cm depth on urea and ammonium N transferred to floodwater.





13. Effect of placement sequence of prilled fertilizer at 5 cm depth on urea and ammonium N transferred to floodwater.

14. Major avenues for N transfer to floodwater during prilled urea placement at 5 cm depth in flooded Maahas clay.

by diffusion 1 day after embedding was relatively small, but continued to increase slightly for 2 and 3 days.

9. Nitrogen diffusion through soil into floodwater, when fertilizer was embedded at 5 cm, was almost equal for all fertilizer materials (Figs. 8b, 9b), indicating that a 5-cm placement depth may be adequate in Maahas clay to minimize N transfer for all three materials.
10. Experiments on delayed fertilizer release of 5, 10, and 15 days were inconsistent (Fig. 10), perhaps because of experimental or analytical errors. It is obvious, however, that N diffusion through soil that had settled for 5, 10, and 15 days was quite small, because the maximum floodwater N level never exceeded a value of 4 ppm for USG or prilled fertilizer.
11. Minimizing fertilizer-water contact during all three phases of deep placement – transit, placement, and covering – would be highly effective for reducing fertilizer loss in flooded fields.
12. Dry fertilizer incorporation followed by flooding increases fertilizer use efficiencies because water dissolves the fertilizer and transfers it deep into the soil. This practice simulates a deep placement effect, thereby minimizing physical transfer of fertilizer granules or solution to the floodwater.
13. In sandy soils with high percolation rates, controlled irrigation techniques may be effective for deep placing fertilizer through irrigation water.
14. Use of low-cost prilled fertilizer coatings such as starch, clay, or oils, which could inhibit fertilizer dissolution in water during the placement and covering operation, may be an economic method for improving fertilizer use efficiencies in flooded fields.
15. Eliminating floodwater for 3 to 4 days prior to fertilizer application followed by flooding may result in a deep placement effect and improve fertilizer use efficiencies.
16. Major N transfer to floodwater occurs during the first 2 or 3 days after fertilizer application. Perhaps deep placement in unsaturated soil 1 or 2 days after draining, and delaying flooding for 2 to 3 days may improve fertilizer use efficiency.
17. Incorporation of fertilizer in a drained soil and delaying flooding till 2 or 3 days after incorporation may be more effective in improving fertilizer use efficiency than incorporating in fields with a substantial amount of water followed by immediate flooding.

IMPLICATIONS FOR APPLICATOR DESIGNS

Most applicators developed until now have not actually placed all the fertilizer deep in the soil because a large part entered the floodwater during the placement operation. This seems to be the main reason for the high degree of variability in field performance of applicators rather than the generally suspected site and soil differences.

Past efforts to develop deep placement applicators have focused on fertilizer-soil interactions. Findings of this study indicate that fertilizer dissolution and movement of fertilizer solution play a major role in increasing N transfer to floodwater in flooded fields. Thus, machines that cover the deposited fertilizer in the placement zone, or otherwise minimize movement of fertilizer and fertilizer water solution from the furrow bottom to the floodwater surface, would substantially improve fertilizer use efficiencies.

CONCLUSIONS

The major channels for fertilizer transfer to floodwater during placement are a) fertilizer dissolution during transit to furrow bottom and b) upward movement of fertilizer granules or solution to the floodwater during furrow closing. These two avenues are so important that in some cases N transfer to floodwater through them almost equals that of broadcast application. Transfer caused by poorly sealed furrows or diffusion in freshly puddled or settled soils is relatively small.

The high degree of variability in the field performance of the available deep placement applicators seems primarily due to excessive N transfer to floodwater during placement rather than to soil and site differences.

The findings of this study are important not only to the design of deep placement applicators but to the overall issue of fertilizer use efficiencies in wetland rice production. The key to improving urea fertilizer use efficiency may depend on keeping the floodwater N level low. Minimizing or blocking the various channels of N transfer through appropriate design of deep placement applicators is one approach to the problem. Research is also needed on fertilizer application and its interaction with different water management practices. Such research may lead to alternate solutions which would substantially improve urea fertilizer use efficiencies without resorting to the more labor-consuming operations of fertilizer incorporation or deep placement. The methodology developed in this study could be effectively utilized for developing such alternate fertilizer application techniques.

It seems that the physical interactions of urea fertilizer and water during deep placement are not fully understood. Further research is needed on fertilizer-soil-water interactions and on the dynamics of fertilizer solutions under different soil and water regimes

Development of commercially viable deep placement applicators for prilled urea fertilizer is essential to increasing paddy production. It is a rare opportunity for agricultural engineers to play an important role in increasing rice production and in raising the living standards of Asian farmers.

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