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Effects of fertilizer price on feasibility of efficiency improvement: Case study for an urea injector for lowland rice

M. van Noordwijk[1,2] and J. H. M. Scholten[1]
[1]*DLO-Research Institute for Agrobiology and Soil Fertility, P.O. Box 129, 9750 AC Haren, the Netherlands;* [2]*Present address: ICRAF-S. E. Asia, P.O. Box 161, Bogor 16001, Indonesia*

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Abstract

Efficiency improving techniques, such as the introduction of a urea injector for lowland rice production, appear to lead to higher yields, lower fertilizer use and less environmental pollution at the same time. If farmers are free to decide on the amount of fertilizer they use, economic rationality leads to a choice between using the improved technique for saving fertilizer while obtaining the same yield, for increasing yield (at the same fertilizer rate) or for a mixed strategy (a slightly higher yield and a different fertilizer rate). The 'economic optimum fertilizer rate' was calculated with a simple yield model for a low and a high fertilizer application efficiency to predict which strategy would be best for the farmer

Calculations for a 'standard' data set for lowland rice show that the greatest benefit from an increase in application efficiency by urea deep placement instead of broadcast application can be expected when a marginal efficiency of about 9 kg rice per kg fertilizer N is used for determining the fertilizer rate. For a marginal efficiency of less than 6, savings on fertilizer are the main benefit of efficiency improvement; for higher marginal efficiencies yield increases become the main component of total benefit; for marginal efficiencies above 9, fertilizer use will increase when a more efficient technique is used, but increased yields compensate for their costs. In the four countries where a manually operated pneumatic urea injector was tested (Togo, Bangladesh, Indonesia and Ivory Coast) the price ratio of rice and fertilizer N ranged from 1.1 to 2.5. Even when a 'risk-avoidance' multiplier of 2 is used, we may conclude that fertilizer prices were too low relative to rice to make optimum use of the existing techniques for efficiency improvement. An equation is derived for estimating the price ratio at which the probability of farmer acceptance of techniques for improving fertilizer use efficiency is highest.

Introduction

Improvement of fertilizer use efficiency m[illegible]e beneficial from an environmental (less pollution) as well as from an economical point of view (lower fertilizer costs and/or higher yields). Improving fertilizer use efficiency is thus important for any government which wants to feed its population, protect its environment and allow a decent income to its farmers. Achieving all these goals, however, does not only depend on technical possibilities; economic policies and price levels may determine whether or not efficiency improvements which are technically possible are actually used. If farmers are free to determine the amount of fertilizer they use, the price ratio between fertilizer and harvested produce determines whether techniques leading to improved efficiency will be used primarily for yield increase at the same fertilizer input level, for reductions in fertilizer use at the same yield level or for a change in both yield and fertilizer rate.

In lowland rice production considerable losses of fertilizer nitrogen occur when urea fertilizer is applied to the surface. Deep-placement of urea in the anaerobic mud may decrease these losses substantially (Wetselaar, 1985). Deep-placement can be achieved manually (supergranules, briquettes) at a considerable labour

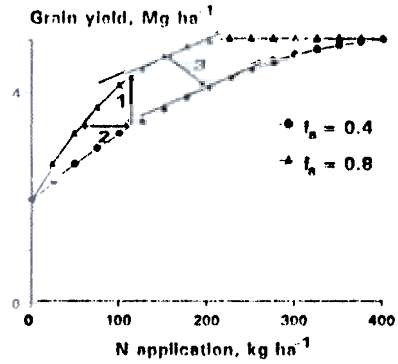

Fig. 1. Expected response of grain yield to N application if two application techniques are used with different efficiencies. Three types of comparison are shown: 1. yield increase at constant N application, 2. fertilizer saving at constant yield and 3. combined effects if for each system an economically optimum fertilizer rate is used, based on the same marginal efficiency (= slope).

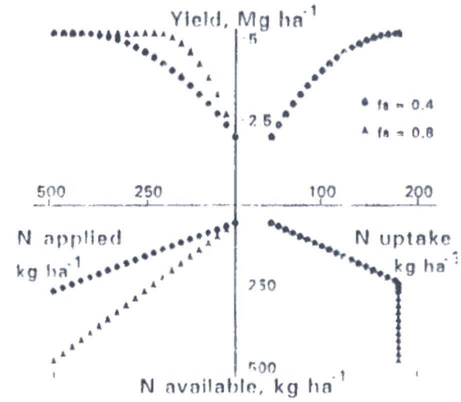

Fig. 2. Four-quadrant representation of fertilizer experiments with two techniques, differing in application efficiency, but leading to the same uptake and utilization efficiency.

cost. A range of technical devices for deep-placement have been developed and tested under field conditions (O'Brien *et al.*, 1985). Although a higher application efficiency can thus be achieved, widespread farmer adoption of these techniques has not occurred (Makken and Scholten, 1991).

A relatively simple manually operated pneumatic urea injector was developed and tested under field conditions (Scholten, 1992). In field experiments a comparison was made between injected and surface applied urea at the nationally recommended N rate and at half of that rate. The experiments were carried out in four countries: Ivory Coast, Togo, Bangladesh and Indonesia. In most of the experiments a yield increase was found when the injector was used. In an economic analysis this yield increase was found to cover the additional labour cost of about 20 hour per ha and a 'pay-back period' was calculated, assuming a reasonable cost per injector (Makken and Scholten, 1991). As this 'pay-back period' was often less than one season, the conclusion seemed to be justified that use of the injector would be beneficial to the farmer and lead to higher rice yields. Reduced pollution by the improved efficiency – in this case especially reduced emission of the greenhouse gas N_2O as a byproduct of denitrification – is viewed as an additional benefit, not considered in the above economic evaluation.

The evaluation of Makken and Scholten (1991) was based on fixed fertilizer rates. The economic analysis and the positive conclusions about the chances of farmer acceptance of the urea injector may change, however, if farmers are free to decide the amount of fertilizer they apply. In this article we present a simple evaluation of the economically rational use of efficiency-improving techniques, and the effects of price ratios on the choice between not using the technique, using it for yield increase and using it to reduce fertilizer use. The evaluation will be based on a strongly schematized view of the technical aspects of the efficiency improvement.

Figure 1 shows three ways of comparing production systems with two fertilizer application efficiencies: 1. yield increase at constant fertilizer rate, 2. fertilizer saving at constant yield, and 3. combined effects if an economic optimum fertilizer rate is used in each system. In this article this third approach will be quantified. Makken and Scholten (1991) and Scholten (1992) considered mainly the first type of comparison.

Yield model

The yield response to N fertilizer application of field crops (Fig. 2) can be analyzed by considering: 1. the relationship between fertilizer application and the amount of available N in the soil, 2. the relationship between the amount of available N in the soil and the amount absorbed by the crop, 3. the relationship between the amount of N absorbed and the dry matter production of the crop and 4. the relationship between total dry matter production and harvested yield. Each of these four relations determines an aspect of the overall fertilizer use efficiency (Van Noordwijk and De Willigen, 1986): 1. application efficiency, 2. uptake efficiency, 3. utilization efficiency and 4. harvest index.

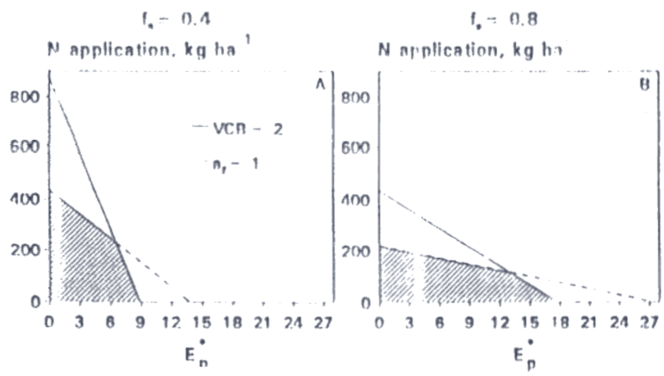

Fig. 3. Effect of the fertilizer rice price ratio E_p^* on two constraints on fertilizer application rate: a marginal efficiency a_r = 1.0 (equation 6) and a total value cost ratio (VCR) = 2.0 (equation 10). A: f_a = 0.4, B: f_a = 0.8. N application rates in the shaded area meet both criteria.

Van Noordwijk and Wadman (1992) presented a simple model based on linear forms of relationships 1, 2 and 4 and a quadratic form of relationship 3 (Fig. 2). If no fertilizer is applied a yield Y_0 will be obtained, equal to:

$$Y_o = 2F_pN_s - \frac{F_p^2N_s^2}{Y_m} \qquad (1)$$

where: Y_m = maximum yield when N is not limiting [kg ha^{-1}], F_p = plant efficiency in producing yield per unit available N in the soil [kg yield per kg N available], N_s = amount of N available in soil from sources other than fertilizer [kg ha^{-1}]. The plant efficiency, F_p, consists of three components:

$$F_p = \frac{f_u f_h}{C_m} \qquad (2)$$

where: C_m = required N concentration in biomass for maximum yield [kg kg^{-1}], f_u = fertilizer uptake efficiency or amount of N absorbed per unit available N in the soil [kg kg^{-1}], f_h = harvest index or grain yield per unit biomass [kg kg^{-1}]. When fertilizer is applied the expected yield Y_F is:

$$Y_F = 2F_p(N_s + f_aN_f) - \frac{F_p^2(N_s + f_aN_f)^2}{Y_m} \qquad (3)$$

f_a = fertilizer application efficiency or increase in available amount of N in the soil per unit fertilizer N applied [kg kg^{-1}], N_f = amount of N added as fertilizer [kg ha^{-1}]. By equating dY_F/dN_f to a marginal efficiency E_p (see appendix), a 'maximum economic yield' Y_e can be derived as:

$$Y_e = Y_m\left[1 - \left\{\frac{E_p}{2f_aF_p}\right\}^2\right] \qquad (4)$$

where: E_p = required marginal efficiency of fertilizer application [kg yield per kg N applied]. The second term in equation 4 indicates the potential yield which is not economical to achieve given the economic conditions and the efficiency of the crop and the application technique. Note that Y_e is independent of N_s; in the derivation we assumed N_s to lead to a below-maximum yield. The marginal efficiency E_p can be regarded as a product of the price ratio E_p^* of fertilizer and yield products and the required marginal returns on investment, a_r:

$$E_p = a_rE_p^* \qquad (5)$$

where: E_p^* = price ratio of fertilizer and yield products [kg kg^{-1}], a_r = required marginal return on invested capital, which is based on the interest paid on fertilizer investment, on the uncertainty of prices for the harvested produce and on the risks of general crop failure (a_r > 1.0). The 'economic optimum' fertilizer rate N_e which is needed to obtain Y_e is equal to (see appendix):

$$N_e = \frac{Y_m}{f_aF_p}\left\{1 - \frac{E_p}{2f_aF_p}\right\} - \frac{N_s}{f_a} \qquad (6)$$

Equation 6 consists of three terms. The first term indicates the N supply necessary to obtain maximum yield (not limited by N), the second term indicates the fertilizer saved by aiming at an optimum rather than maximum yield, and the third term reduces the fertilizer requirement by accounting for the inherent soil fertility. Equation 6 may lead to negative fertilizer application rates depending on soil supply N_s and required marginal efficiency E_p. Negative values should be interpreted as zero.

In discussing the economics of fertilizer use often the concept of a value cost ratio (VCR) is used, which is defined as the yield increase (yield with fertilizer Y_F minus Y_0) divided by the costs of fertilizer.

$$VCR = \frac{Y_F - Y_0}{N_f E_p^*} \qquad (7)$$

The VCR decreases with increasing fertilizer use. When a fertilizer rate is calculated on the basis of a marginal efficiency E_p, the VCR equals:

$$VCR = \frac{f_a F_p}{E_p^*}\left\{1 - \frac{F_p N_s}{Y_m}\right\} + \frac{a_r}{2} \qquad (8)$$

It is often assumed that for farmer adoption of fertilizer use VCR should be at least 2.0. This can be achieved by a specific choice of a_r:

$$a_r = 2\left\{2 - \frac{f_a F_p}{E_p^*}\right\}\left\{1 - \frac{F_p N_s}{Y_m}\right\} \qquad (9)$$

The fertilizer rate at which a VCR of 2 is obtained, N_{vcr2}, can be calculated by combining equations 5, 6 and 9:

$$N_{vcr2} = \frac{2}{f_a}\left\{\frac{Y_m}{F_p} - N_s\right\}\left\{1 - \frac{E_p^*}{f_a F_p}\right\} \qquad (10)$$

and the corresponding yield Y_{vcr2} is:

$$Y_{vcr2} = Y_m\left\{1 - \left(\frac{2E_p^*}{f_a F_p} - 1\right)^2\left(1 - \frac{F_p N_s}{Y_m}\right)^2\right\} \qquad (11)$$

A combination of the two criteria can now be made. If the marginal efficiency should be at least 1.0 and the overall value cost ratio at least 2, the best fertilizer rate is the minimum of N_{vcr2} and N_e. Figure 3 shows the highest acceptable fertilizer N rates for the VCR and the marginal return criterion as a function of E_p^*, for two values of the application efficiency, f_a. Fertilizer rates chosen in the shaded area are 'economically feasible' according to both criteria. For low values of E_p^* the required marginal efficiency is restricting the fertilizer level, for higher price ratios the required VCR is determining the result. The two criteria are equal for a price ratio E_p^* equal to:

$$E_p^* = \frac{2 f_a F_p (Y_m - N_s F_p)}{(4 - a_r) Y_m - 4 N_s F_p} \qquad (12)$$

A higher application efficiency (compare Fig. 3a, b) means that less fertilizer is needed to reach maximum yields (N rate for $E_p^* = 0$), but also means that fertilizer rates are less sensitive to E_p^* (the negative slope is less) and the E_p^* value for which at least some fertilizer use is economically feasible increases. A next step is to compare two production systems, differing in application efficiency.

Model effects of increased application efficiency

We will first consider the situation where the marginal efficiency is determining the fertilizer rate chosen. An increase in the fertilizer application efficiency from f_{a1} to f_{a2} has an effect on both yield and N rate if the economically optimum fertilizer rate is used for both situations. The yield increase ΔY can be derived from equation 4 as:

$$\Delta Y = Y_m\left\{\frac{E_p}{2F_p}\right\}^2\left[\frac{1}{f_{a1}^2} - \frac{1}{f_{a2}^2}\right] \qquad (13)$$

Because all terms of this equation are positive, we can conclude that improved application efficiency ($f_{a2} > f_{a1}$) always leads to a yield increase, unless E_p is zero (fertilizer is free of charge). The yield increment will increase proportional to the square of the marginal efficiency E_p. The change in economic fertilizer rate ΔN_e can be derived from equation 6 as:

$$\Delta N_e = \frac{Y_m E_p}{2F_p^2}\left\{\frac{1}{f_{a1}^2} - \frac{1}{f_{a2}^2}\right\} + \left\{\frac{Y_m}{F_p} - N_s\right\}\left\{\frac{1}{f_{a1}} - \frac{1}{f_{a2}}\right\}$$

This equation assumes that both N_e values are positive and should be modified if either one is zero. The change in economic fertilizer rate can be positive or negative, depending on E_p and N_s. For low E_p (cheap fertilizer) ΔN_e will be negative and less fertilizer will be used; for high E_p, more fertilizer will be used if the application efficiency is increased, especially in a situation where fertilizer use with the inefficient application technique is not economically feasible. For a certain value of

E_p the change in application efficiency will not affect fertilizer use ($\Delta N_e = 0$). This value can be obtained by solving for Ep after equating (14) to zero:

$$E_p(0) = \frac{2f_{a1}f_{a2}F_p}{(f_{a1}+f_{a2})}\left\{1 - \frac{N_sF_p}{Y_m}\right\} \tag{15}$$

The total economic benefit B from an increase in application efficiency f_a can be obtained from:

$$B = \Delta Y - E_p^* \Delta N_e - C \tag{16}$$

or, by substituting equations (13) and (14),

$$B = \frac{Y_m a_r E_p^{*2}}{2F_p^2}\left\{\frac{a_r}{2} - 1\right\}\left\{\frac{1}{f_{a1}^2} - \frac{1}{f_{a2}^2}\right\} + E_p^*\left\{\frac{Y_m}{F_p} - N_s\right\}\left\{\frac{1}{f_{a1}} - \frac{1}{f_{a2}}\right\} - C \tag{17}$$

where C is any additional cost of the new technique, also expressed in equivalents of yield per ha. For $a_r = 2$, the first term cancels and B becomes a linear function of E_p^*, Y_m, F_p, N_s and the efficiency improvement. The relative contribution of the yield increase and change in fertilizer use to the total benefit can be evaluated by comparing equations 13 and 14 to equation 17. By differentiating B with respect to the required marginal efficiency E_p^*, the value of E_p^* (m) can be found (see appendix) for which the efficiency improvement has a maximum effect (for $a_r < 2$).

If $a_r = 1$, this maximum is found for $E_p^*(m) = E_p(0)$, as defined in equation 15,

$$E_p^*(m) = \frac{2f_{a1}f_{a2}F_p}{(f_{a1}+f_{a2})a_r(2-a_r)}\left\{1 - \frac{N_sF_p}{Y_m}\right\} \tag{18}$$

and thus coincides with the point where the economically optimum fertilizer rate is the same for the two application techniques. If $a_r > 2$, E_p^* (m) becomes negative.

If the fertilizer rate for both applications is determined by the constraint on the VCR, the yield increase is:

$$\Delta Y_{vcr2} = \frac{2Y_mE_p^*}{F_p}\left\{1 - \frac{F_pN_s}{Y_m}\right\}^2 \left\{\frac{2E_p^*}{F_p}\left(\frac{1}{f_{a2}^2} - \frac{1}{f_{a1}^2}\right) - \left(\frac{1}{f_{a2}} - \frac{1}{f_{a1}}\right)\right\} \tag{19}$$

and the change in fertilizer rate:

$$\Delta N_{vcr2} = 2\left\{\frac{Y_m}{F_p} - N_s\right\}\left\{-\frac{E_p^*}{F_p}\left(\frac{1}{f_{a2}^2} - \frac{1}{f_{a1}^2}\right) + \left(\frac{1}{f_{a2}} - \frac{1}{f_{a1}}\right)\right\} \tag{20}$$

When both the VCR and the marginal return criterion are used, it is best to numerically determine the optimum N level and yield for each application efficiency (compare Fig. 3) and then compare the values for the two systems. Algebraic formulations become rather complex.

Case study for pneumatic urea injector

The main effect of deep-placement of urea in lowland paddy fields compared with surface application is a reduction of N losses immediately after fertilizer application. In terms of the yield model, this means an increase in the fertilizer application efficiency. There is, as yet, no reason to assume that the mode of application has an effect on the maximum yield attainable, or on the parameters C_m, f_u, f_h, or N_s.

The following parameter values were used in the calculations (see also Table 1): f_a is 0.4 for surface application and 0.8 for deep placement with the injector; $f_u = 0.8$ (the 'apparent fertilizer recovery' at moderate fertilizer rates $f_a \times f_u$ is thus 0.32 for surface application and 0.64 for deep-placement, which is in the observed range (Scholten, 1992), $f_h = 0.5$ (short-straw varieties), $N_s = 50$ kg ha^{-1}, $C_m = 0.018$ (based on general relationship between C_m and Y_m/f_h (Van Noordwÿle and Wadman, 1992); Van Keulen and Wolf (1986) give 0.0075 as minimum concentration for rice, which leads to $C_m = 0.015$) and $Y_m = 5\,000$ and 7 500 kg ha^{-1}. Calculations were made for E_p in the range 0–25 kg rice per kg N fertilizer.

Results

Figure 4A shows the effect on maximum economic yield if the application efficiency is doubled, as a function of the required marginal efficiency E_p, for $a_r = 1$. If E_p is zero, the maximum economic yield is equal to the maximum physical yield for both application efficiencies. If E_p is low (cheap fertilizer) it is economical to aim at nearly the maximum physical yield and an improved efficiency has little effect on the maximum

Table 1. Symbols used and parameter values in the 'standard case'

a_r = risk aversion factor, marginal benefit: cost ratio	[$ $^{-1}$]	
B = total benefit of improved application efficiency	[kg ha^{-1}]	
C_a = additional costs of the more efficient technique	[kg ha^{-1}]	
C_m = required N concentration in biomass for maximum yield	[kg kg^{-1}]	0.018
E_p = marginal efficiency of fertilizer application	[kg kg^{-1}]	0–20
E_p^* = price ratio of fertilizer and yield products	[kg kg^{-1}]	0–10
f_{a1} = fertilizer application efficiency when broadcast	[kg kg^{-1}]	0.4
f_{a2} = idem, for technique 2 (injection)	[kg kg^{-1}]	0.8
f_u = fertilizer uptake efficiency	[kg kg^{-1}]	0.8
f_h = harvest index or yield per unit biomass	[kg kg^{-1}]	0.5
F_p = yield per unit N available in the root zone	[kg kg^{-1}]	22.2
N_s = amount of available N in the soil from other sources than fertilizer	[kg ha^{-1}]	50
N_e = 'economic optimum' fertilizer rate	[kg ha^{-1}]	
N_{VCR2} = fertilizer rate for which the value cost ratio is 2	[kg ha^{-1}]	
VCR = value cost ratio of fertilizer application	[$ $^{-1}$]	
Y_m = maximum yield	[kg ha^{-1}]	5000
Y_e = yield at an 'economic optimum' fertilizer rate N_e	[kg ha^{-1}]	
Y_F = yield at a given fertilizer rate F	[kg ha^{-1}]	
Y_{VCR2} = yield at a fertilizer rate for which VCR is 2	[kg ha^{-1}]	

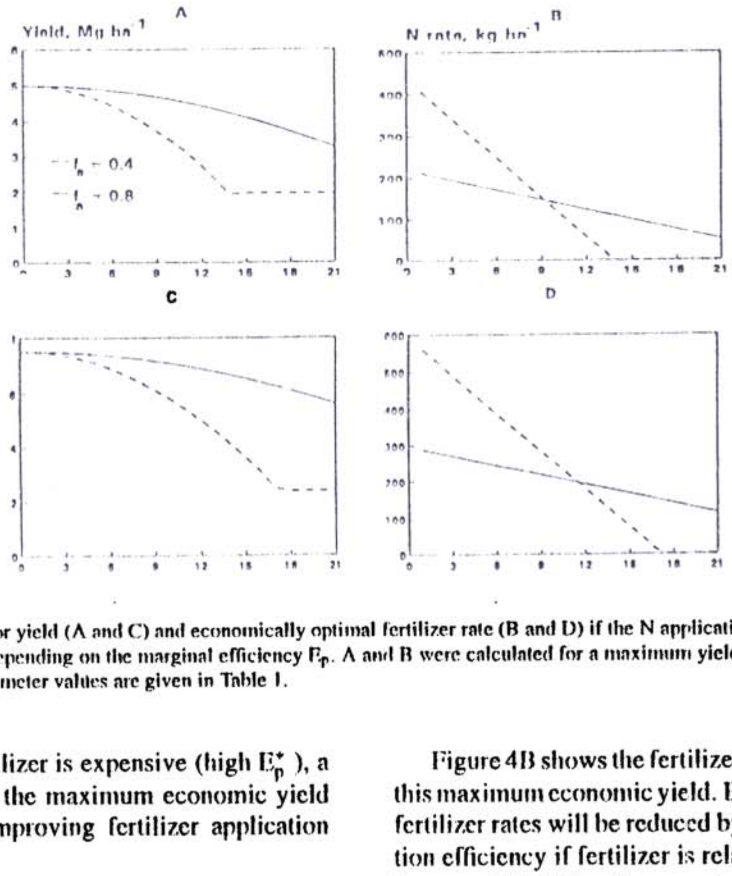

Fig. 4. Model predictions for yield (A and C) and economically optimal fertilizer rate (B and D) if the N application efficiency f_a is increased from f_{a1} = 0.4 to f_{a2} = 0.8, depending on the marginal efficiency E_p. A and B were calculated for a maximum yield of 5000 kg ha^{-1}, C and D for 7500 kg ha^{-1}; other parameter values are given in Table 1.

economic yield. If fertilizer is expensive (high E_p^*), a substantial increase of the maximum economic yield can be achieved by improving fertilizer application efficiency.

Figure 4B shows the fertilizer rates needed to obtain this maximum economic yield. Economically optimum fertilizer rates will be reduced by an increased application efficiency if fertilizer is relatively cheap, but may increase if fertilizer is expensive. For the parameters

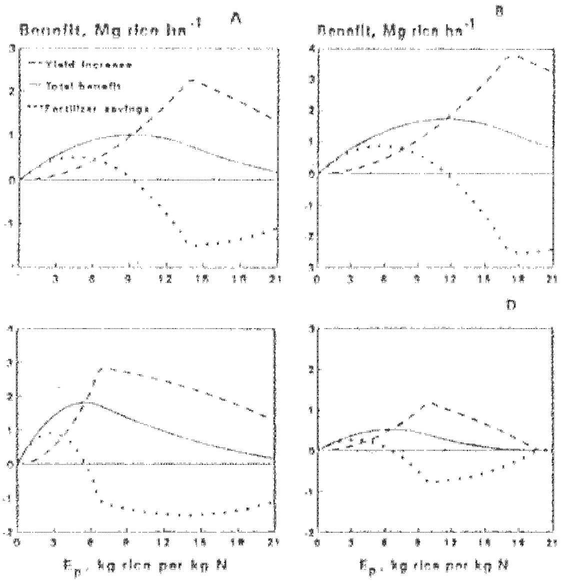

Fig. 5. Total economic benefit (yield increase and fertilizer saving) of an improved application efficiency, expressed in kg rice per ha, as a function of E_p. A, standard case, B, Y_m = 7500 (instead of 5000) kg ha^{-1}, C, fertilizer application efficiency of broadcast, f_{a1} = 0.2 (instead of 0.4), and D, soil mineral N supply N_s = 100 (instead of 50) kg ha^{-1}; other parameter values are given in Table 1.

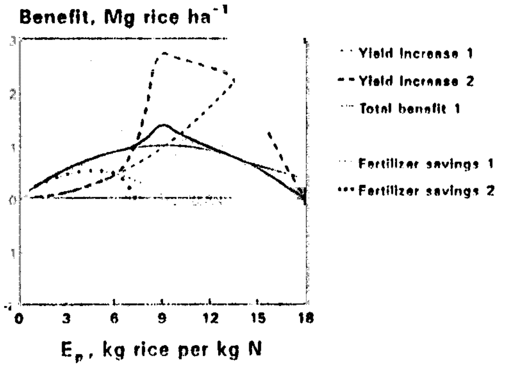

Fig. 6. Total economic benefit (standard parameter set) of efficiency improvement if the fertilizer rate is chosen on the basis of a marginal return criterion alone (situation 1, equal to Fig. 5A) or in combination with a value-cost ratio of 2.0 (situation 2).

used, the transition point (E_p(O), compare equation 15) is found at a marginal efficiency of 9.2 kg rice per kg N.

Figures 4C and 4D show the effect of a higher maximum yield level on the relationships shown in figure 4A and 4B, respectively. The overall shape of the curves is the sáme, but maximum economic yield and the economically optimum fertilizer rate are increased for each value of E_p. The point where both techniques lead to the same economically optimum fertilizer application is shifted to a slightly higher marginal efficiency, as indicated by equation 15. The marginal efficiency where it becomes uneconomical to apply any fertilizer by broadcasting is also shifted to a higher value.

Figure 5A shows the total benefits of increased application efficiency from 0.4 to 0.8, expressed in kg rice per ha, for the standard parameter set (Table 1). The economic yield is increased for any value of E_p above zero; at low E_p values the amount of fertilizer is reduced, for E_p above 9 it is increased (and shown as negative fertilizer saving in the graph). The greatest benefit from an increase in application efficiency is obtained for a marginal efficiency of about 9. For a marginal efficiency of less than 6 savings on fertilizer are the main benefit; for a marginal efficiency above 9 increased yields compensate for increased fertilizer use when urea is injected in stead of broadcast. The rice equivalents of additional labour costs of using the injector (C in eq. 14) could be represented as a horizontal line in Fig. 5 (not shown); based on 20 h additional labour costs per ha and a labour price of 5 kg rice per hour, this would amount to 100 kg ha^{-1}. For a value of E_p < 1, the additional labour costs exceed the expected benefit.

Figures 5 B-D show the effect of modified parameter values on the overall benefit and its components. A higher maximum yield level (Fig. 5B), 7500 in stead of 5000 kg ha^{-1}, leads to greater absolute benefits of efficiency improvement (note the modified scale on the Y axis), and also to a larger marginal efficiency where the total benefit reaches its maximum value. The marginal efficiency where the two methods have the same economically optimum fertilizer rate is also the value where the total benefit of efficiency improvement has its maximum (eq. 15). When the broadcast application efficiency is only 0.2 (instead of 0.4 as in the standard case), the total benefit is higher (Fig. 5C) and reaches a maximum at a lower marginal efficiency (about 6). When the N supply from the soil is increased (Fig. 5D), from 50 to 100 kg ha^{-1}, the required fertilizer rates and the benefits of efficiency improvement are less. This graph shows that at high marginal efficiency E_p no benefit of efficiency improvement can be obtained, as fertilizer use is not economical at either application efficiency.

Figure 6 shows the effect of adding the VCR criterion to the comparison, for the standard case. The effects on the total benefit are relatively small. At low E_p^* values the results are equal as the marginal return criterion determines the fertilizer rate for both efficiencies. Around the $E_p(O)$ value (eq. 15) the required VCR restricts fertilizer use for the low application efficiency and the benefit of increasing the application efficiency is slightly higher than in the previous situation. Using the VCR criterion has a pronounced effect on both fertilizer use and yield benefit for E_p^* values in the range 9–14, but a small effect on the total benefit for the farmer.

Discussion

The model predicts that the prices of fertilizer and rice have a major impact on whether or not the introduction of an efficiency-improving technique is worthwhile, and if so, whether yield increase or fertilizer savings are the main basis of an overall benefit to the farmer. The model calculations suggest a number of conditions under which benefits of applying the more efficient technique are clear:

- situations with very low application efficiencies from broadcast fertilization, as may be found where irrigation water flows continuously through the rice fields; this situation may be found on mountain terraces,
- situations with high actual fertilizer/rice price ratios or values of a_r,
- situations with high maximum yield levels (no other limiting factors),
- situations with a low inherent soil N supply,
- situations with low labour costs.

In the four countries where the pneumatic urea injector was tested the price ratios E_p^* were approximately: 1.1 in Togo (65 CFA per kg urea (46% N), 126 CFA per kg rice (after milling)), 1.8 in Bangladesh (5 Taka per kg urea, 6 Taka per kg rice), 2.3 in Indonesia (200 Rp per kg urea, 175–200 Rp per kg rice) and 2.5 in Ivory Coast (102 CFA per kg urea, 75–100 CFA per kg rice) (Makken and Scholten, 1991). At marginal efficiencies E_p between 2 and 5 (based on an a_r of 2) in the four countries the expected benefit of introducing an efficiency-improving technique (such as an urea injector) is the equivalent of 400–800 kg rice per ha for the standard parameter set and consists largely of fertilizer savings. For a high maximum yield (Y_m = 7500 kg ha^{-1}) the total benefit is 500–1100 kg rice per at E_p between 2 and 5.

Qualitatively, the main conclusions on the effects of the price ratio would also hold if the shape of the N response curve differs; spatial variability in N supply in the field may lead to a slower approach of the maximum yield and a situation where the marginal efficiency is even more important (Van Noordwijk and Wadman, 1992).

O'Brien *et al.* (1987) estimated that compared to surface application, deep-placement of urea in lowland rice in Indonesia (based on application of urea supergranules) reduced the economically optimum rate of N use by 25% and increased yield by less than 10%. The fertilizer rates used by farmers with the standard technique were nearly high enough to obtain the maximum possible yield, according to this study.

The 'first impression' of the economic feasibility of the urea injector by Makken and Scholten (1991) and their positive assessment of the injector was based on measured yield increases when the nationally recommended fertilizer rate was injected rather than surface-applied. In some countries, however, the recommended fertilizer rate is lower than the economically optimum for surface-applied fertilizer; e.g. in Bangladesh recommendations aim at a total benefit cost ratio of 4 to 5. The previous evaluation (Makken and Scholten, 1991) did not consider the freedom of farmers to use more (or less) fertilizer than this recommended amount. Wherever freedom exists and farmers may maximize profits, the effect of an effiency-improving technique on fertilizer rates should be taken into account. Rice farmers in countries with low fertilizer rice price ratios may be fully justified in **not** using all the technical innovations that can improve fertilizer application efficiency. Increasing the fertilizer application efficiency probably reduces the harmful impact of agriculture on the environment, although under certain (extreme) conditions it may increase fertilizer use and so the loss of fertilizer to the environment (per ha. not per unit rice produced). If governments wish to stimulate efficient fertilizer use, the introduction of technical improvements should be stimulated by maintaining price ratios between fertilizer and food products, which on the one hand allow fertilizer to be used for increasing food production, but on the other hand make it worthwhile to increase efficiency and reduce wastage. The $E_p(O)$ value (eq. 6) may form a first guideline for this price ratio.

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Appendix

Equation (4) can be derived from (3) by the following steps. First, the derivative of the yield Y_F curve with regard to fertilizer application N_f is equated to E_p:

$$\frac{dY_F}{dN_F} = 2F_p f_a - \frac{2F_p^2 f_a N_s}{Y_m} - \frac{2F_p^2 f_a^2 N_f}{Y_m} = E_p \quad \text{(A3)}$$

By re-arranging we obtain:

$$N_s + f_a N_f = \left(1 - \frac{E_p}{2 f_a F_p}\right)\frac{Y_m}{F_p}$$

Substitution in (3) and rearranging we obtain equation (4). By rearranging equation (A2) we obtain equation (6).

The price ratio for which the increase in application efficiency has the largest effect can be obtained by differentiating equation (17) with respect to E_p^* and solving for $dB/dE_p^* = 0$:

$$\frac{dB}{dE_p^*} = -\frac{E_p^* a_r Y_m}{2F_p^2}\left(2 - a_r\right)\left(\frac{1}{f_{a1}} \quad \frac{1}{f_{a2}}\right)\left(\frac{1}{f_{a1}}\right.$$
$$+\frac{Y_m}{F_p}\left(1 - \frac{N_s F_p}{Y_m}\right)\left(\frac{1}{f_{a1}} \quad \frac{1}{f_{a2}}\right) = 0$$

By re-arranging this equation can be solved for E_p^* (m) and leads to equation (18).