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INTERACTION BETWEEN FERTILIZER AND WEED CONTROL METHODS IN PHILIPPINE UPLAND RICE: ESTIMATES FROM FARMERS' FIELDS

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Dennis T. O'Brien and Edwin C. Price[1]

ABSTRACT

The interaction of fertilizer and weed control on upland rice is examined using data from farmers' fields in Cale, Batangas, Philippines. Regression estimates of technical relationships between upland rice yield and inputs indicated that yield response to hand weeding increases with N application and that application of more than 75 kg N/ha will decrease yield unless hand weeding is done. Alternate combinations of fertilizer and hand weeding, and of fertilizer, hand weeding, and herbicides, that achieve equivalent yields are shown. Profit-maximizing levels of inputs, yields, and net returns were estimated and compared with mean constrained levels (set at present rates of each input use) for farm owners and tenants. Although profit-maximizing levels of inputs are different from constrained input levels, the marginal net benefits imply rates of return on additional investment of about 27% for owners and 21% for tenants. These rates are likely to be unattractive to Cale farmers faced with uncertain weather. Several suggestions are made for improving and extending the study.

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INTERACTION BETWEEN FERTILIZER AND WEED CONTROL METHODS IN PHILIPPINE UPLAND RICE: ESTIMATES FROM FARMERS' FIELDS

Considerable research has evaluated the effect of weeds and weed control on rice yields, but most work is done on lowland varieties and takes little account of the interaction between inputs, especially those between fertilizer and weed control. In this paper, data collected from upland rice farmers in Cale, Batangas, Philippines, are used to estimate the production relationships in rice under farmer management. The effects of chemical weed control, with different hypothesized rates of weed reduction, on crop response to hand weeding and applied nitrogen are also estimated.

The paper has three main sections. Hypothesized technical relationships in upland rice production are presented in the first two sections. Although weed management in upland rice in the Philippines is emphasized, the theoretical relationships developed are applicable to other crops in other areas. Empirical estimates of the hypothesized relationships are determined and validated in the third section.

HYPOTHETICAL TECHNICAL RELATIONSHIPS

The effect of weeds on crop yield and net value is neither direct nor simple. Crop development and, ultimately, crop yield and net return are affected by the physical environment – levels of insect, disease, and weed infestations; methods and levels of insect, disease, and weed management; and other cultural practices. The actions of each of these on the crop are rarely independent of the effects of the others.

Figure 1 shows a hypothetical set of interactions. Climatic factors such as drought stress and typhoons directly affect crop development. They also affect the crop indirectly by influencing the levels of insects, diseases, and weeds and by hindering the performance and effectiveness of weed, insect, and disease control and other cultural operations. Weather is also a source of stochastic variation or uncertainty in crop yield because of the variability of its direct and indirect effects on annual yield. Land quality (e.g., topography, drainage, irrigation, chemical and soil physical properties) affects crop development directly and indirectly by influencing cultivation operations and other management practices.

The two-way arrows in Figure 1 connecting weed level and crop development show their competitive relationship. This balance is affected exogenously by environmental effects on weed and crop development. It is also affected by the level and type of weed management used by the farmer. The weed management techniques shown in Figure 1 are separated into primary and secondary methods (Moody 1978). Primary methods aim to reduce weed population and competition with the crop, thereby increasing crop yield. Secondary methods have other objectives, of which weed management may or may not be the most important. Secondary weed controls, such as land preparation, water management, and crop rotation, may also directly reduce weed level. Other secondary methods, however, such as planting method, type of cultivar, and planting density, may increase the competitive advantage of the crop. Fertilizer application may increase both weed and crop growth or, by increasing the competitive advantage of the crop or weeds, limit the development of one or the other.

Primary weed control methods

Primary weed control methods include manual and chemical methods of reducing weed population.

Manual weed control. Most Cale farmers use hand weeding to control rice weeds. Hand weeding labor varies from 0 to 600 h/ha, depending on weed incidence and constraints on hand weeding that can be done (availability of hired and family labor, cash for wages, and weather and field conditions during the hand weeding period).

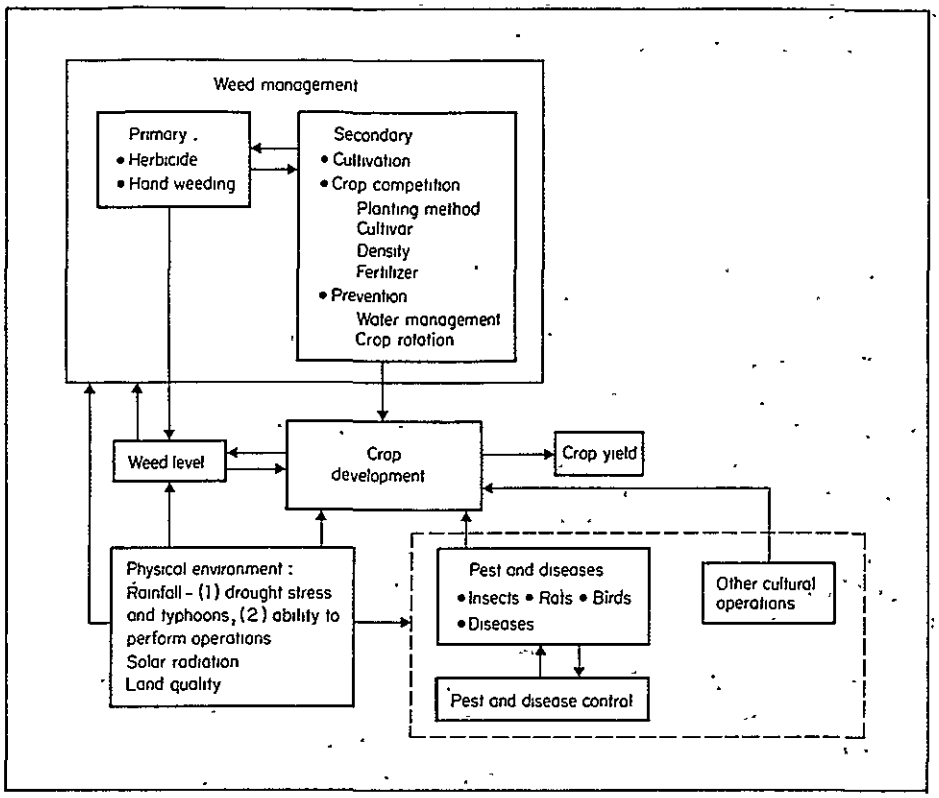
Chemical weed control methods (herbicides). Adoption of herbicides has been slow in the Philippines and Asia, particularly in upland rice and in most upland crops. Cale farmers are aware of herbicides, but few have tested them and none use them regularly. Personal interviews with Cale farmers showed they were reluctant to use herbicides because of the effect of herbicides on other crops, cost, need to still do hand weeding, health hazards, and lack of information on herbicide use.

Secondary weed control methods

Land preparation. Land preparation is an important weed management technique. Moody (1978) suggests that the weed control effect of land preparation is a more important determinant of crop yield than are good physical soil conditions.

Postplant cultivation. Postplanting cultivation is done in Cale to thin rice plants and reduce weeds. If land preparation has been adequate, postplanting cultivation is more for rice thinning than weed control.

Fertilizer. In a weed-free crop, the effect of fertilizer on crop yield is reasonably apparent. If all factors remain constant, increased fertilizer generally increases yield. If, as is normal, weeds grow with the crop, then the effect on crop yield is not as direct. Crop response to fertilizer depends on competition between the crop and weeds for available soil nutrients and water. The growth of both may increase, or that of one may increase while that of the other decreases.



1. Relationship between weed management, weed level, physical environment, other factors, and crop yield.

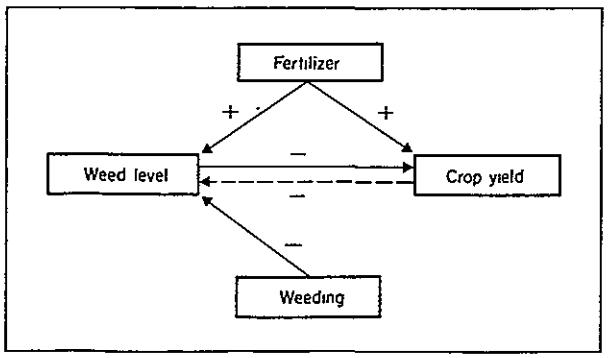
If weeding is done, the final effect of fertilizer on crop yield is altered further. The interaction of fertilizer, weeds, weeding, and crop yield is summarized in Figure 2.

Other secondary methods

Other secondary weed controls alter the competitive balance between weeds and crop.

Method of planting. Compared to direct-seeded rice, transplanted seedlings have a competitive advantage over newly germinating weeds, and also permit earlier flooding for weed control. Dry seeding is practical in Cale and is one of the reasons for more severe weed problems in upland than lowland areas.

Water management. Weeds are generally a more serious problem in upland rice because they cannot be controlled through water management. In contrast, flooding lowland fields prevents weed seeds from germinating and kills some weed species that have already germinated.



2. Effect of fertilizer on crop yield as influenced by weeds and weeding.

Crop variety. Most Cale farmers grow the traditional rice variety Dagge, which competes better with weeds than do most high-yielding varieties (HYVs) because of its early seedling vigor, greater height, drooping leaves, and consequent shading effect. Its longer growth duration also makes it more competitive with weeds, and its deep-rooting nature facilitates mechanical weeding.

A lower ability to compete with weeds, lack of awareness of alternative methods of weed control, and greater susceptibility to moisture stress are among the major reasons for poor acceptance of the new varieties in upland areas. The low competitiveness of new cultivars indicates that associated weed management systems must be developed before HYVs can be more widely adopted in these environments. When weeds are controlled, yields from HYVs are considerably higher than those for traditional varieties.

Plant density. Greater plant density makes the crop more competitive with weeds. However, a very high plant density may reduce weed level but decrease yields because of competition among rice plants and a possible increase in insect and disease problems.

Crop rotation. Crop rotation and the various cultural practices used for different crops help reduce the buildup of specific weeds.

MATHEMATICAL MODEL

The relationships between weed level, weed management, and crop yield shown in Figures 1 and 2 can be formally specified in a set of mathematical functions. A model that specifies the set of relationships between traditional weed control methods, weed incidence, and crop yield is presented first. It will then be altered to reflect the hypothesized effect of herbicide treatments.

Traditional weed management

Equation 1 and Figure 3 show the hypothesized effect of weeds on crop yield. Equation 1 also shows the direct effect of fertilizer application on crop yield.

$$Y = a - bW^2 + fN + gN^2 \quad (1)$$

where Y is crop yield; W is weed incidence; N is level of applied nitrogen fertilizer; and a, b, f, and g are parameters to be estimated.

The effects of hand weeding and nitrogen application on weeds are assumed, for simplicity, to be linear:

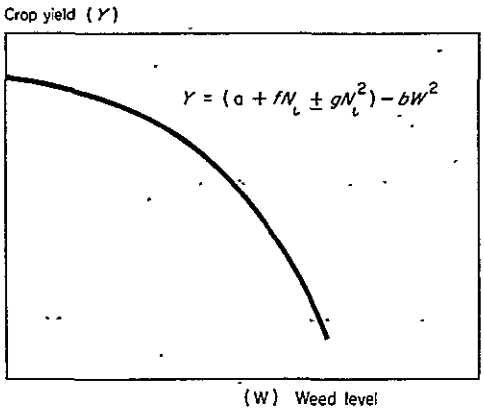
$$W = d - kH + mN \quad (2)$$

where H is man-hours of hand weeding and d, k, and m are parameters.

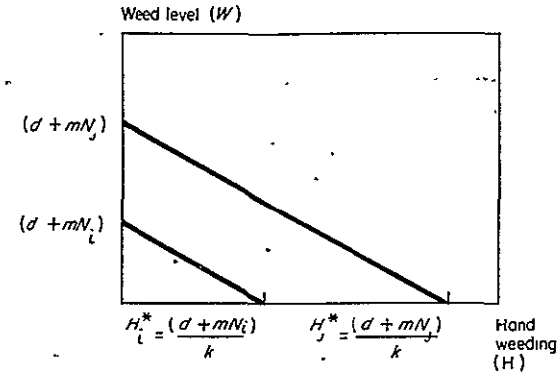
The coefficient d in Eq. 2 is an index of potential weed level — the level of weeds that would develop without crop competition, if fertilizer were not applied and if no hand weeding were done. The magnitude of the coefficient is determined exogenously in the mathematical model by such factors as the direct effect of environment, previous cultural practices, and location.

The coefficient k is the reduction of weed level per hour of hand weeding. Figure 4 shows the relationship between weed level, fertilizer, and hand weeding. Figure 4 shows the assumed constant rate of weed reduction (k) per hour of hand weeding up to $H = H^*$. Levels of hand weeding above H^* do not affect weed level as weed level cannot be less than zero.

A more complete specification of Eq. 2 would have included the effect of the crop on weed level. Inclusion of this aspect, however, would have made the following analysis more complex and perhaps would have detracted from its expository nature.



3. Hypothesized effect of weed level on crop yield for a specified level of applied nitrogen (N_i).



4. Effect of hand weeding on weed level for constant specified levels of land preparation and postplant cultivation, and two levels of fertilizer ($N_j > N_i$).

The direct effects of fertilizer application on crop yield and the yield reduction effect of weeds are reflected in Eq. 1. Equation 2 accounts for the effect of manual weed control and fertilizer application on weed level. To account for the direct and indirect effects of the primary and secondary weed management methods on crop yield, it is necessary to substitute the expression for W from Eq. 2 into Eq. 1 and derive the production function:

$$Y = a - b\,(d - kH + mN)^2 + fN + gN^2 \quad (3)$$

Equation 4 is obtained from Eq. 3 by expanding the quadratic component and rearranging terms:

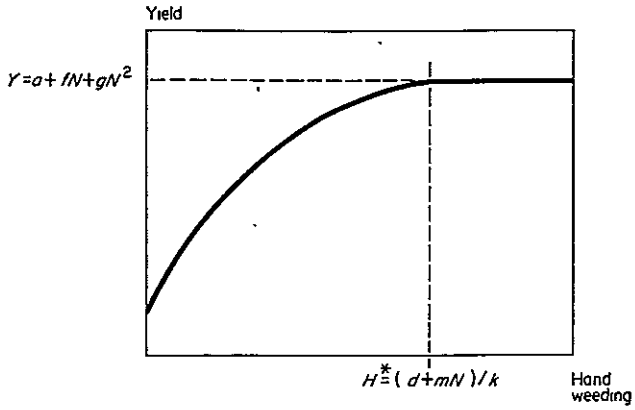
$$Y = (a - bd^2) + 2\,bdkH + (f - 2\,bdm)\,N - bk^2H^2 + (\pm g - bm^2)\,N^2 + 2\,bkmHN \quad (4)$$

Equation 4 explicitly accounts for the effects of hand weeding and fertilizer application on crop yield. The effect of other secondary weed management methods, other cultural practices, and climatic conditions are implicit in the function. The magnitude of the coefficients in Eq. 1 and 2 and, hence, the values of the composite coefficients of Eq. 4 are affected by those factors. Equation 4 therefore accounts either explicitly or implicitly for all the effects shown in Figures 1 and 2, except that of crop development on weed level.

The relationship between hand weeding and crop yield is shown in Figure 5. The decreasing marginal physical productivity of hand weeding (MPP_H) as the level of weeding is increased is caused by the increasing marginal yield reduction due to weeds specified in Eq. 1. When the weed level is zero, at $H = H^*$, the MPP_H is also zero. At hand weeding levels greater than those which reduce the weed level to zero ($H \geq H^*$), weeding is assumed to have no effect on crop yield; hence, the horizontal section of Figure 5. This assumption is specified as:

$$Y = a + fN + gN^2 \text{ for } H \geq H^* \quad (5)$$

Without manual weeding (H = 0) the effect of applied nitrogen on crop yield depends on the response of the crop (f and g) and weeds (m) to nitrogen, the level of weeds (d),



5. Yield as a function of hand weeding.

and the effect of weeds on crop yield (b). The net effect of these factors is shown in the composite coefficients [$(f-2bdm)$ and $(\pm g-bm^2)$] on N and N^2 in Eq. 4.

The effect of hand weeding on crop response to nitrogen is determined by the magnitudes of the coefficient on the interaction term (HN) in Eq. 4. The positive sign on the interaction term implies a complementary relationship between applied nitrogen and weeding. Complementary inputs are defined as those in which $\partial(\partial Y/\partial N)/\partial H$ is positive. For an implicit quadratic production function, this derivative is the value of the coefficient on the interaction term for the two inputs. If inputs are complementary, the marginal productivity of one increases as the level of the other increases.

The relationship between hand weeding and crop yield for two levels of applied nitrogen ($N_1<N_2$) is shown in Figure 6. Figure 6a shows the case where the net effect of fertilizer application, before any weeding effect is measured, is positive, that is, where the direct positive response of the crop to applied fertilizer is greater than the indirect negative effect. Figure 6b shows the case where the indirect effect is greater than the direct effect.

For the case in Figure 6a, crop yield will always increase with the higher level of fertilizer (N_2). For a crop with fertilizer and weeding response as shown in Figure 6b, the higher fertilizer level will cause lower crop yields unless more than H' level of weeding is done.

Chemical weed control

To this point the mathematical model has been discussed for traditional weed control methods. While herbicides are an alternative control, they will most likely be combined with traditional technology, rather than replace it.

In the mathematical formulation, herbicide application is assumed to proportionately reduce the potential weed level d in Eq. 2. The weed reduction effect or herbicide effectiveness depends on the kind of weeds and the rate, time, method, and type of herbicides applied. If p is defined as the proportion of weeds remaining after herbicide treatment, then pd is the potential weed level after a field has been sprayed with a herbicide. The lower the value of p, the more effective is the herbicide treatment. If p equals one, then there is no weed reduction from herbicide treatment, or no herbicide was applied. If p equals zero, then herbicide application has killed all weeds and weed regrowth is assumed to be insufficient to affect crop yield.

The rate of weed reduction from hand weeding is assumed to be constant and unaffected by weed level. Consequently, no alteration due to the effect of herbicide application is made to the coefficient on hand weeding k in Eq. 2.

Because herbicide application reduces the weed population, the response of the weed biomass to fertilizer application will be proportionally reduced. This effect is accounted for by adjusting the coefficient on nitrogen in Eq. 2 from m to pm.

These effects are shown in the following respecified formulation of Eq. 2:

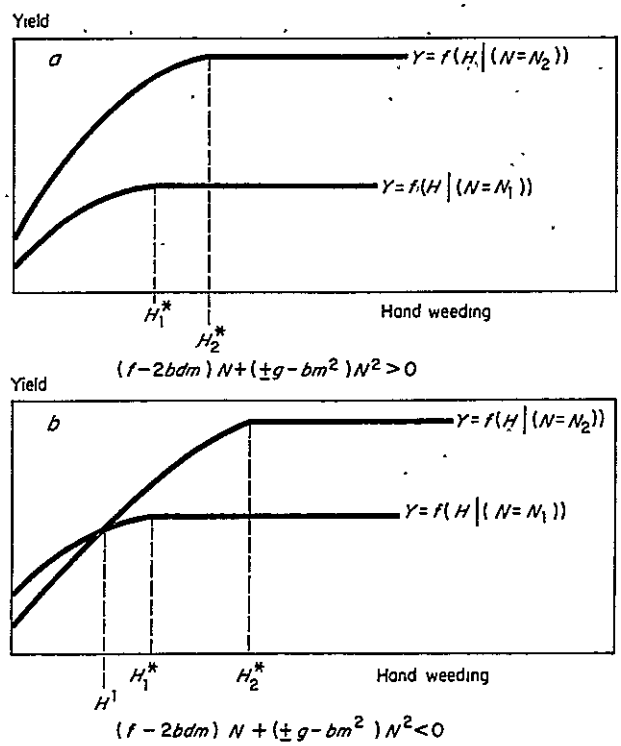
$$W = pd - kH + mN \qquad (6)$$

The level of hand weeding, when a herbicide is also used, that reduces the weed level to zero is shown in Eq. 7 as a function of applied nitrogen and herbicide effectiveness:

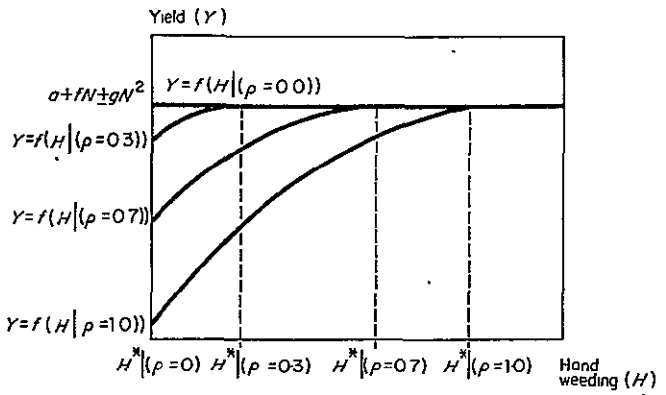
$$H^*_{p'} = p'(d+mN)/k \qquad (7)$$

$H^*_{p'}$ is the amount of hand weeding that reduces the weed population to zero, given that a herbicide with an effectiveness level of p' has been applied. Levels of hand weeding above $H^*_{p'}$ have no effect on weed level, as weed level cannot be less than zero.

The effect of herbicide treatment on crop yield is specified by the production function. This is determined by sub-



6. Effect of hand weeding on crop yield for two levels of applied nitrogen.



7. Effect of hand weeding on crop yield for several herbicide effectiveness levels and a specified rate of applied nitrogen (N_i).

stituting the expression for W from Eq. 6 into Eq. 1 in the same manner that Eq. 2 was substituted into Eq. 1.

$$Y = (a - bp^2d^2) + 2bpdkH + (f - 2bp^2dm)N - bk^2H^2 + (+g - bp^2m^2)N^2 + 2bkpmHN \quad (8)$$

The relationship between hand weeding and crop yield, as specified in Eq. 8, for several herbicide effectiveness levels and a fixed rate of applied nitrogen (N_i) is shown in Figure 7. The maximum crop yield with a zero effective weed level is $(a + fN_i + gN^2_i)$. The same assumption about yields for weeding levels above $H^*_{p'}$, as assumed for the traditional technology in Eq. 5, is applied here:

$$Y = a + fN + gN^2 \text{ for } H \geq H^*_{p'} \quad (9)$$

EMPIRICAL ESTIMATION OF TECHNICAL RELATIONSHIPS

Data

Ordinary least squares (OLS) estimation procedure was used to estimate the parameters of a hypothesized production function relating rice yield to the inputs listed in Table 1 under existing technology. Unless otherwise stated, rice refers to unhusked grain (palay). Data for 56 farmers' plots, collected in the 1975-76 crop season by the economics staff of IRRI's Cropping Systems Program, were used. These data are summarized in Table 1.

Regression results

The estimated production function is for the traditional Dagge variety. Most farmers in the area grew only this variety in 1975, and none of the plots in the sample were planted to HYV. The empirically estimated regression equation is shown in Table 2. It confirms the hypothetical relationships in the preceding section, Eq. 4.

One quarter (R^2 = 0.25) of the variability in observed crop yield is explained by the derived equation. In the cross-sectional data used in the analysis, several other factors that were not accounted for in the equation but may be important in explaining differences in crop yield are:

- a measure of the management skill of each farmer (Management skill includes such items as effectiveness of each mechanical and manual weeding operation, time of fertilizer application, and control of insects and other pests.),
- the effect of location on the microclimate of each plot, and
- timing of operations other than planting.

Mechanical operations

The separate effects of each preplant or postplant mechanical operation were also tested but could not be isolated. The estimated regression coefficients for these variables had low statistical significance and signs that were inconsistent with those that were expected. Composite variables of mechanical operations were also tested and yielded similar results.

Planting date

A planting date variable is included in the estimated equation to reflect the effects of weather conditions on rice crops planted at various times. Delayed planting in 1975-76 reduced rice yield. Yield is estimated to decrease by 8 kg/ha for each day after day 112 of the year that planting is delayed.

Hand weeding

The estimated function includes three variables that show the effect of hand weeding. As hypothesized, hand weeding improves crop yield but improvement decreases as the level of weeding increases; that is, the coefficient for hours of hand weeding is positive, while that for hand weeding squared is negative. The results also show that the response of the crop to fertilizer or hand weeding is complemented by increased levels of the other; that is, the coefficient for fertilizer times hours of hand weeding is positive.

Table 1. Summary of upland rice data for 56 farmers' plots, 1975-76, Cale, Batangas.[a]

Variable	Mean	Standard deviation
Preplant harrowing (no.)	0.81	0.85
Preplant plowing (no.)	2.32	2.77
Postplant harrowing (no.)	2.55	1.11
Use of lithao (no.)	2.40	0.86
Hand weeding (h/ha)	234.63	235.02
Nitrogen applied as urea (kg/ha)	62.16	25.79
Planting date (days from beginning of year)	129.92	13.49
Crop yield (kg/ha)	1827.96	583.48

[a]The original data set contained 64 observations. Three were deleted because they had extreme levels of applied nitrogen (238, 241, and 515 kg/ha). Two were removed because of unusually high yields (3,960 and 3,150 kg/ha) for the factor use levels reported. Fifty-nine remained in the set used in the regression analysis. Three further observations were eliminated because the observed Y_i values deviated by more than two standard deviations from the estimated Y_i value.

Table 2. Regression equation for traditional rice, Cale, Batangas, 1975-76.[a]

Variable	Coefficient	t-value	Level of statistical significance
Intercept	985.1224	2.4405	0.018[b]
Planting date variable[c]	-8.1054	1.3536	0.182[b]
Hours of hand weeding	1.7145	1.4557	0.076
Hours of hand weeding squared	-0.0019	1.9569	0.028
Kilograms of applied nitrogen	19.8300	1.6263	0.055
Kilograms of nitrogen squared	-0.1333	1.1048	0.105
Nitrogen X hours of hand weeding	0.0105	0.7783	0.220
$R^2 = 0.25$ F = 2.701	Significance level on F = 0.024		

[a]Dependent variable is kg palay/hectare. [b]The level of statistical significance is for a two-tailed t-test. The significance levels on all other variables are for one-tailed tests. [c]The earliest rice planting date in 1975-76 was day 113. Therefore, the value of the planting date variable for a crop planted on day 113 is 1.

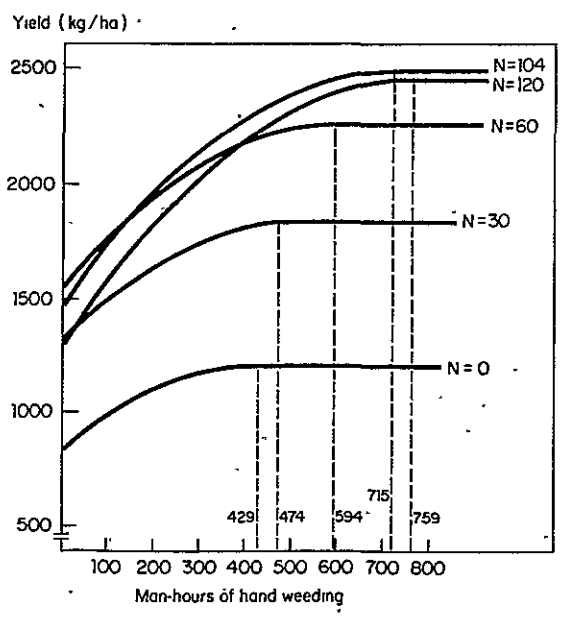
Fertilizer

Level of applied nitrogen had a positive yield effect. Marginal productivity decreased over the range of levels included in the data set. These findings were consistent with the hypotheses of positive coefficient for fertilizer and negative for fertilizer squared.

The complete set of coefficients of the hypothetical functional relationships for traditional weed control technology can be derived from the estimated regression equation (Table 2). By first substituting the average value of the planting date variable and combining this with the estimated intercept term, the production function of the form specified in Eq. 4 is obtained:

$$Y = 839.8 + 1.715H + 19.830N - 0.002H^2 - 0.133N^2 + 0.011NH \quad (10)$$

This equation contains a set of composite coefficients of known values.



8. Yield response functions for specified levels of nitrogen and variable levels of hand weeding.

$$a - bd^2 = 839.8 \quad (11)$$
$$2bdk = 1.715 \quad (12)$$
$$f - 2bdm = 19.830 \quad (13)$$
$$bk^2 = 0.002 \quad (14)$$
$$g + bm^2 = 0.133 \quad (15)$$
$$2bkm = 0.011 \quad (16)$$

Eq. 11-16 contain seven unknown coefficient values. There are insufficient equations in the set to allow the unique values of the coefficients to be determined. By specifying 100 as the index of potential weed level (d), unique values for the other coefficients can be calculated[2]. By substituting these derived values into Eq. 1 and 2, the following estimates are obtained:

$$Y = 1235.3 - 0.040W^2 + 24.686N - 0.118N^2 \quad (17)$$
$$W = 100 - 0.217H + 0.614N \quad (18)$$

The empirically estimated response function (Eq. 10) for five levels of applied nitrogen is shown in Figure 8. The curves in this figure are empirical estimates of those in Figures 6a and 6b.

The yield-maximizing levels of hand weeding and applied nitrogen, determined[3] from the estimated production function (Eq. 10), are 715 man-hours and 104 kg/ha. Figure 8 includes the yield response curve for different levels of hand weeding when 104 kg N/ha is applied. Figure 8 shows that 104 kg N/ha gave the maximum yield of 2,484 kg palay/ha at 715 man-hours of hand weeding per hectare and that the yields for all levels of hand weeding when 104 kg N/ha is applied are greater than those for the corresponding amounts of hand weeding when 120, 30, and zero kg N/ha are applied. However, when 104 kg N/ha is applied the response function is more than when 60 kg N/ha is used only at plus 180 man-hours of hand weeding/ha.

Figure 8 shows that when 120 kg N/Ha is applied, yield is less than that for 60 kg N/ha unless more than 374 man-

[2]Because of the proportional changes in b, k, and m and the unaltered values of a, f, and g for different specified values of d, the values of the composite coefficients, when adjusted for the effect of herbicide application (p), do not depend on the specified value of d.

[3]$\frac{\partial Y}{\partial N} = \frac{\partial Y}{\partial H} = 0$

hours/ha of hand weeding can be done. The yield obtained when 120 kg N/ha is applied is also less than that when 30 kg N/ha is used, unless hand weeding is at least 11 man-hours per hectare.

In summary, Figure 8 shows that

- Intercept values increase as the level of applied nitrogen is increased up to 75 kg/ha. Above this level, the intercept decreases; that is, rice yields increase initially with increased nitrogen, even without weeding. At applied nitrogen levels greater than 75 kg/ha, however, yields will decline as more nitrogen is applied unless some hand weeding is done.
- The slope of the curves for a specified level of hand weeding is greater for larger amounts of nitrogen, that is, the increase in yield due to additional weeding is greater in fields that receive higher rates of fertilizer.
- The level of hand weeding that gives the highest yield for a specified level of applied nitrogen increases as the level of nitrogen is increased.
- The maximum yield that can be obtained for a specified level of nitrogen increases as the amount of nitrogen is increased to 104 kg/ha. Above that level, the maximum attainable yield decreases.

The interaction between applied nitrogen and hand weeding in Figure 8 is shown in another way in Figure 9. A series of isoquants (lines of equal rice yield) is mapped in input space. The figure shows the combinations of applied nitrogen and hand weeding that give specified rice yields. For example, 1,500 kg of rice could be obtained with 20 kg of nitrogen and 213 man-hours of hand weeding (point f) or with 40 kg of nitrogen and 38 man-hours of hand weeding (point g).

Lines ab and ad mark the rational zone of production. Within the area abcd, the levels of both inputs required to obtain a specified yield are less than those required to obtain the same yield outside the rational zone.[4]

Figure 9 shows that to obtain the maximum yield of 2,484 kg, 715 man-hours of hand weeding and 104 kg N are required.

Production functions when chemical weed control is included

The empirically estimated set of hypothesized functional relationships when a herbicide is introduced is

$$Y = a - bw^2 + fN - gN^2 \quad (1)$$

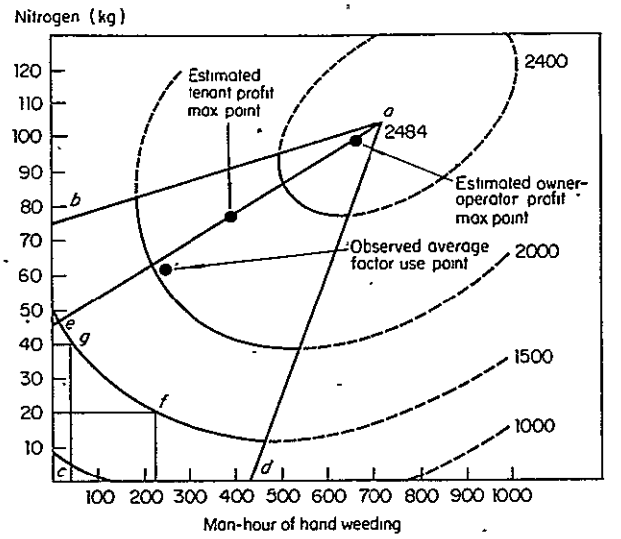
$$Y = 1235.3 - 0.040W^2 + 24.686N - 0.118N^2 \quad (19)$$

$$W = p(d+mN) - kH \quad (6)$$

$$W = p(100 + 0.614N) - 0.217H \quad (20)$$

$$Y = (a-bp^2d^2) + 2bpdkH + (f-2bp^2dm)N - bk^2H^2 - (g+bm^2p^2)N^2 + 2bpkmHN \quad (8)$$

[4] This is true if the perceived or expected production relationship, at the time the decision about factor use levels is made, is the same as the actual or observed relationship in a season. It is the observed relationship for a cross-section of farmers in one season that is shown in Figures 8 and 9. A rational producer would operate within the rational zone of the production function that he expects to occur.



9. Production isoquants (lines of equal yield) for different levels of hand weeding and applied nitrogen.

$$Y = (1235.3 - 400p^2) + 1.715pH + (24.686 - 4.912p^2)N - 0.002H^2 - (0.118 + 0.015p^2)N^2 + 0.011pHN \quad (21)$$

The empirically estimated composite coefficients of Eq. 21 for values of p from 0 to 1 are shown in Table 3.

Figure 10 shows rice yield as a function of hand weeding for the average level of applied nitrogen (Table 1) and specified herbicide effectiveness levels. If 62 kg N/ha were applied, the estimated maximum rice yield that could be obtained in 1975 is 2,306 kg/ha. The hand weeding required to obtain this yield at that nitrogen level decreases from 623 man-hours to 125 hours for traditional technology (p = 1.0) if a herbicide with an effectiveness level of 0.2 is applied and 0.0 if one with a value of p equal to 0.0 is used.

Hand weeding and fertilizer combinations for specified yields (isoquants) when a herbicide that removes 60% of the weeds (p = 0.4) is applied are shown in Figure 11. The maximum yield (2,484 kg/ha) obtained when all weeds are removed and 104 kg N/ha is applied equals that with no herbicide (Fig. 9). However, the level of hand weeding required to reduce the weed level to 0.0 and maximize yield, when 104 kg N/ha is applied, at 296 man-hours per hectare, is less than half of that required without herbicide. The effect of a herbicide on fertilizer and hand weeding levels required to obtain the maximum or other specified yields can be seen by comparing the positions of the isoquants and rational zones of production in Figures 9 and 11.

Net returns from manual weed control

The estimated profit-maximizing levels of factor use and associated yields and net returns for different assumed economic and tenure conditions when a herbicide is not used are shown in Table 4. The profit-maximizing levels of hand weeding and applied nitrogen are higher than the average levels used by Cale farmers (Table 1). Possible reasons for this are:

Table 3. Empirically estimated rice production functions for traditional and integrated weed control, Cale, Batangas, 1975.[a]

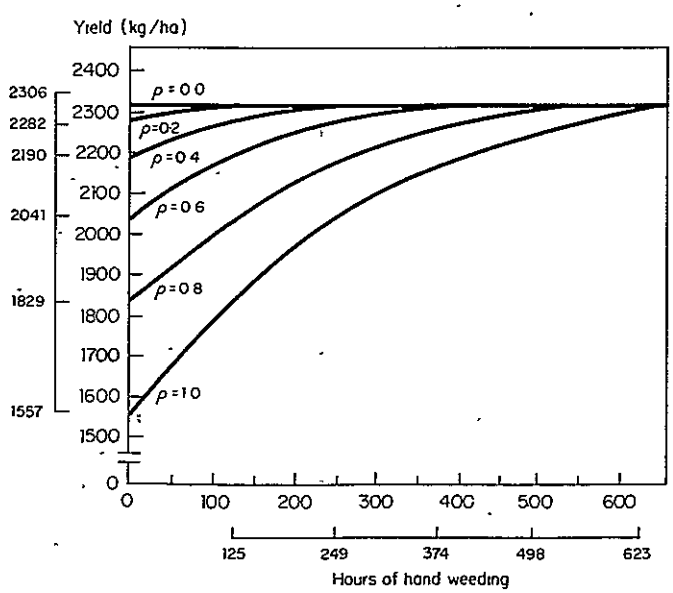
Productive factor	Production coefficients at indicated values of p					
	1.0[b]	0.8	0.6	0.4	0.2	0.0[c]
Intercept	839.8031	982.1909	1092.7650	1172.0414	1219.5041	1235.3250
Hours of hand weeding (H)/ha	1.7145	1.3716	1.0287	0.6858	0.3429	0
Kilograms nitrogen (N)/ha	19.8300	21.5782	22.9379	23.9092	24.4919	24.6862
Hours of hand weeding squared (H^2)/ha	−0.0019	−0.0019	−0.0019	−0.0019	−0.0019	−0.0019
Kilograms nitrogen squared (N^2)/ha	−0.1333	−0.1279	−0.1237	−0.1208	−0.1190	−0.1184
Hand weeding-nitrogen interaction (HN)	0.0105	0.0084	0.0063	0.0042	0.0021	0

[a]Dependent variable is kg unhusked rice/ha. [b]1.0 is the case of traditional weed control technology or no herbicide effect. [c]p = 0.0 is the case of weed reduction to the level that weeds do not affect crop yield.

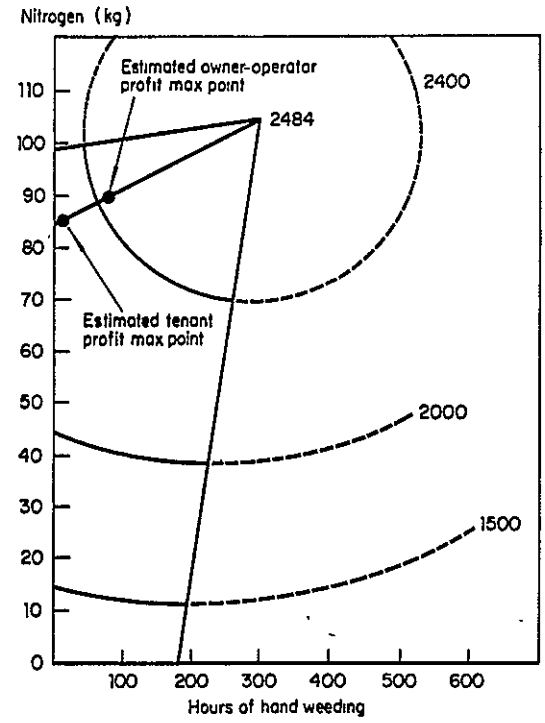
- weather constraints on available weeding time,
- lack of cash or credit with which to hire additional labor or purchase more fertilizer, and
- farmer response to uncertainty about late season moisture stress and typhoon effects.

Although the differences in factor use levels are substantial, differences in estimated yield and net return are not. The difference in net return between an owner-operator with unconstrained fertilizer and hand weeding and one using average levels of nitrogen and hand weeding is ₱123/ha. For a tenant, this difference is ₱36. To obtain these increases in net return, an owner-operator must spend an additional ₱447/ha and a tenant ₱169/ha. Under the uncertain weather conditions of Cale, it is unlikely that many farmers would choose to incur the large additional cost for the small increase in net return. 1975 was an 'average' year.

The *expansion path* (line ea determined for fertilizer and hand weeding prices in 1975) is shown in Figure 9.



10. Rice yield functions for different herbicide effectiveness levels, Cale, Batangas, 1975. Nitrogen applied at 62 kg ha.



11. Production isoquants (lines of equal yield) for different levels of hand weeding and applied nitrogen when a hypothetical herbicide that removes 60% of the weeds (p = 0.4) is applied. Cale, Batangas, Philippines, 1975 data and prices.

The equation of the expansion path is:

$$\frac{\partial Y}{\partial N} p_H = \frac{\partial Y}{\partial H} p_N$$

$$N = 46.11 + 0.08 H$$

where: p_H and p_N are the prices of hand weeding and nitrogen, respectively;
p_H = ₱0.875/h; and
p_N = 2.59 · 1.15 = ₱2.9785/kg.
Refer to Table 3 for specific prices.

Table 4. Estimated constrained and unconstrained profit-maximizing levels of factor use and the associated yields and net returns under different assumed sets of economic and tenure conditions.[a]

Assumed economic and tenure conditions[b]	Hand weeding (man-hours/ha)	Applied nitrogen (kg/ha)	Cost of hand weeding and nitrogen (₱/ha)	Yield (kg/ha)	Yield retained by operator (kg/ha)	Net return[c] (₱/ha)
Owner operator						
Unconstrained hand weeding and nitrogen	640	93	837	2466	1973	2242
Constrained hand weeding	*235*	76	432	2068	1654	2149
Constrained nitrogen	533	*62*	651	2267	1814	2179
Constrained nitrogen and hand weeding	*235*	*62*	390	2011	1609	2119
Tenant operator						
Unconstrained hand weeding and nitrogen	377	77	559	2258	1204	1321
Constrained hand weeding	*235*	71	417	2053	1095	1291
Constrained nitrogen	336	*62*	479	2137	1140	1300
Constrained nitrogen and hand weeding	*235*	*62*	390	2011	1072	1283

[a]The prices are those that prevailed in 1975. The assumed wage rate on hired labor, opportunity cost on family labor was ₱7.00/8-hour day. The price of nitrogen was ₱2.59/kg. The retail price of rice was ₱1.56/kg. The interest rate on cash borrowed to purchase fertilizer was 15%/annum. [b]Both owners and tenants pay one-fifth of the crop to the harvesters. Tenants also pay one-third to the landowner. The constrained levels of hand weeding and applied nitrogen are the average levels reported in Table 1. [c]Net return is gross return (after payment to harvesters and landowner) less the cost of weeding labor and applied nitrogen. The costs of other inputs have not been deducted.

The line shows the levels of factor use that give the highest net returns when total input costs are constrained to various levels. It shows the economically efficient levels of factor use for the set of factor prices that farmers face.

The unconstrained profit-maximizing levels of hand weeding and fertilizer for tenants and owner-operators are shown in Figure 9 (refer also to Table 3). The average factor use levels for the sample of farmers are also shown in Figure 9. They are lower than the unconstrained levels for the tenant and the owner-operator. Possible reasons (resource constraints and risk avoidance) have been discussed However, observed average factor use does lie close to the estimated expansion path, indicating a high level of economic efficiency (Barker 1979).

The average crop yield obtained with the average input levels (1,828 kg/ha, Table 1) is less than that indicated by the estimated production function (2,011 kg/ha, Table 4) for the same input levels. This could be due to specification bias in the estimated regression function or farmer technical inefficiency. That is, individual farmers do not use the inputs (fertilizer and hand weeding) in proportions that take advantage of their complementarity to the extent obtained when a combination of average input levels is applied. Because of the nature of the estimated response function (quadratic and interaction terms), the average yield determined by taking the average of the yields obtained when each input combination is substituted into the response function is different from the yield obtained when the average levels of factor use are substituted into the response function.

Net return with herbicide application

The expansion path when a herbicide with an effectiveness level of $p = 0.4$ is applied is shown in Figure 11. To include higher fertilizer-hand weeding ratios, it has shifted markedly from that shown in Figure 9 for traditional technology.

Table 5. Estimated unconstrained profit-maximizing levels of factor use and the associated yields and net returns when a hypothetical herbicide that removes 60% of the weeds ($p = 0.4$) is used.[a]

Assumed economic and tenure conditions[b]	Hand weeding (man-hours/ha)	Applied nitrogen (kg/ha)	Cost of hand weeding and nitrogen (₱/ha)	Yield (kg/ha)	Yield retained by operator (kg/ha)	Net return[c] (₱/ha)
Owner-operator	96	91	355	2456	1965	2710
Tenant-operator	3	84	253	2331	1243	1686

[a]The prices are for 1975. The assumed wage rate of hired labor or opportunity cost of family labor was ₱7.00/8-hour day. Nitrogen cost ₱2.59/kg. The retail price of rice was ₱1.56/kg. The interest rate on cash borrowed to purchase fertilizer was 15%/year. [b]Both owners and tenants pay one-fifth of the crop to the harvesters. Tenants also pay one-third to the landowner. The constrained levels of hand weeding and applied nitrogen are the average levels reported in Table 1. [c]Net return is gross return (after payment to harvesters and landowner) less the cost of weeding labor and applied nitrogen. The costs of other inputs have not been deducted.

The profit-maximizing levels of factor use for tenants and owner-operators are shown in Figure 11 and Table 5. The unconstrained profit-maximizing yields, shares of yield retained by the operator, and net returns per hectare for owner- and tenant-operators are higher when the herbicide is applied (Table 5) than when it is not (Table 4). The levels of fertilizer used by both owner- and tenant-operators are higher when herbicide is used and the rate of hand weeding is lower.

CONCLUSIONS

This analysis presents a set of hypothetical relationships between fertilizer and manual and chemical weed control and empirically tests them to the extent that available data allowed. Data on the effect of herbicides in farmers' fields were not available. Determination of the empirical relationship between specific herbicides and fertilizer, hand weeding, and crop yield would be a valuable extension of this analysis, particularly in view of the rapidly changing prices of agricultural chemicals and human labor.

The analysis is a simplification of the complex biological relationships that exist between variable weed populations, the rice crop, weed control methods, and the physical environment (Fig. 1). By considering this simple framework, however, some complexities and less apparent response mechanisms have been shown. Possible extensions of the framework developed here would be

- consideration of the effect of hand weeding time and fertilizer and herbicide application.
- inclusion of the effect of the crop on weed level.
- accurate measurement of the level and type of weed population rather than use of the index d in Eq. 2.

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