Land Allocation in HYV Adoption Models: An Investigation of Alternative Explanations

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Microeconomic theory provides four competing explanations for partial land allocation to new and traditional seed varieties in HYV adoption decisions: input fixity, portfolio selection, safety-first behavior, and learning. Testing a general model that contains each as a special case suggests that they are jointly most likely to explain land allocation in the HYV adoption decisions of Malawian smallholders. Yet when each explanation is tested to the exclusion of the others (as is usually the case in the literature), competing hypotheses are individually significant. Results suggest that employing approaches based on single explanations may lead to inappropriately narrow conclusions.

Key words: HYV adoption, land allocation, seed-fertilizer technology.

When farmers in developing countries adopt new seed-fertilizer technology, they often continue to allocate a portion of their crop area to traditional varieties. A farmer's decision to plant both seed types can be explained by any of four competing microeconomic theories of joint production. Three of these—portfolio selection, safety-first or survival algorithms, and farmer experimentation—embody behavioral assumptions. Diseconomies of size with allocable fixed inputs is a fourth, technical explanation.[1]

Theoretical models of seed-fertilizer innovations generally posit one or two of these explanations as the single maintained hypothesis, to the exclusion of alternative explanations.[2] Empirical adoption studies have often used one or two (but not all) of the alternative explanations to explain input allocations that appear to diverge from profit-maximizing outcomes (Lin; Hammer; Pingali and Carlson). This practice raises a major methodological issue in the study of technology adoption. When we postulate one theoretical explanation for adoption of new seed types and test it econometrically with conventional techniques, we either reject or fail to reject the single explanation. If the data support the single explanation but competing explanations are not mutually exclusive, we may erroneously conclude, based on our research results, that other approaches are "wrong."

On the other hand, models that are general enough to contain several theoretical approaches may not be empirically tractable. Consequently, in applied work, we often ignore this philosophical dilemma and proceed by narrowly positing one explanation and attempting to verify it statistically. Often, different studies "reach conflicting econometric conclusions" (even with the same data) and "contradictory hypotheses can coexist" indefinitely (Blaug, p. 261).

Our paper uses farmer adoption patterns in Malawi to construct and test empirically a model for land allocation in seed-fertilizer adoption decisions that contains the competing explanations as special cases. Survey evidence from Malawi has suggested that none of the competing theoretical approaches for land allo-

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[1] A fifth explanation for joint production is economies of scope, which implies that the cost of producing both seed types on the same farm is lower than the costs of producing two seed types by different farmers. Economies of scope are unlikely to occur in the varietal choice context.

[2] Occasionally more than one of the arguments are combined in a joint hypothesis, as in the case of risk aversion with learning (Hiebert; Tsur, Sternberg, and Hochman).

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cation to hybrids and "local" (traditional) maize varieties should be ruled out a priori. Testing competing explanations as nested models within a general model provides statistical evidence that a combination of explanations, rather than any single theoretical approach, best describes land allocation to hybrid seed.

Theoretical Explanations for Land Allocation To Both New and Traditional Seed Varieties

Seed-fertilizer technology is usually considered to be divisible. With divisible technology, risk-neutral farmers who maximize expected profits use only the technology with the highest returns per hectare. That is, all farmers either adopt completely or not at all. In developing countries, seed-fertilizer technologies are often only partially adopted. The theoretical approaches that explain incomplete adoption of new seed types are largely based on the themes of input fixity or rationing, risk and uncertainty, and various forms of market imperfections. Major paradigms are summarized below.

Input Fixity

The short-run fixity of land is an important source of jointness or interdependence of crop production (Shumway, Pope and Nash; Leathers, 1991). In agricultural economies where the supply of inputs or credit is rationed, inputs normally regarded as variable, such as fertilizer, can be considered as quasi-fixed, allocable inputs in the short run. A farmer may choose to cultivate and fertilize both new and traditional seed types even though the optimal choice in the absence of rationing would be to cultivate and fertilize only one seed type. Neither production uncertainty nor risk-averse behavior need be assumed to generate this result. The critical assumptions are that fertilizer quantity is fixed for individual farmers and that yield response functions for the two varieties cross. In other words, at low levels of fertilizer, but not at higher levels, the old variety outperforms the new variety (McGuirk and Mundlak).

Portfolio Selection

Even when technology is neutral to scale, a risk-averse farmer may choose to grow both new and traditional maize types. A number of key models in the adoption literature present land allocation among varieties as a portfolio selection. The extent of land allocated to the new seed type is determined by risk attitudes, the stochastic relationship between the yields of the two seed types, and the effects of scale factors such as wealth and the fixed costs of gathering information (Feder; Feder and O'Mara; Hiebert; Just and Zilberman). The guiding assumption of these models is farmer risk aversion in the Von Neumann-Morgenstern sense.

Safety First Behavior

Safety-first models, which were developed from observations about how producers behave in response to downside risk, can also explain why farmers choose to allocate land to new and traditional seed types. These models postulate that the probability of failing to achieve producer goals constrains producer choice. The decision maker's goals are expressed in terms of a targeted level of a random variable (output, income, or subsistence production). While such models have been used to examine pending bankruptcy, versions of the model have also been used in the agricultural development literature to explain levels of fertilizer use (Bell), land allocation to food and cash crops (Carter and Wiebe; Hammer; Kunreuther and Wright), and how technology choices vary with the sociodemographic characteristics of the farm household when the decision maker's goal is to secure returns large enough to cover subsistence needs (Moscardi and de Janvry).[3]

Farmer Experimentation and Learning

Most formal learning models of farmer adoption have emphasized how farmer beliefs about the technology, the initial skill level or human capital of the operator, or the costs of information gathering affect the time to initial adoption (Feder and Slade; Lindner, Fischer, and Pardey; O'Mara). Models that explicitly show the effects of learning on land allocation are less common. The argument that formal education and learning from experience reduce allocative

[3] Although portfolio selection and safety-first approaches can be characterized as variations within the same class of theoretical models about risk and uncertainty (e.g., Leathers 1990), they are derived from very different observations about human behavior and have often been framed as competing explanations for adoption choices (e.g., Roumasset et al.).

errors (Huffman) implies change in land allocation decisions over time (Hiebert; Kislev and Shchori-Bachrach). Although most models have assumed that (*a*) farmers are risk averse and/or (*b*) the recommended technology generates high payoffs, neither assumption is necessary. Some models have suggested that a risk-neutral farmer may test an innovation even when it is unprofitable to do so—because of the information gained through experimentation (Lindner; Leathers and Smale).

Characteristics of Hybrid Maize Adoption in Malawi

Survey research in Malawi (Smale et al.) suggests that none of the theoretical explanations for farmers' land allocation to maize hybrids and local varieties should be ruled out a priori. Relevant findings are summarized below.

Input Fixity

In Malawi's rainfed agriculture, the package of modern techniques for maize production includes only hybrid seed and fertilizer. With limited private markets for inputs, the dominant diffusion method for inputs has been official credit clubs. Official credit clubs are organized and assisted by extension agents employed by the Ministry of Agriculture. At planting time, input packages of fixed size and composition are distributed to club members free of transport charges. Private sources of production credit are limited. Not only are farmers constrained by credit supply, but regulated distribution mechanisms create a form of input fixity for hybrid seed and fertilizer.

Portfolio Selection

The shape and relative position of per hectare net returns distributions for hybrids and local varieties suggest that farmers may be able to reduce overall riskiness of returns by growing a portfolio of maize types. The distributions also cross at lower net returns levels, indicating that farmers who seek to avoid downside risk may choose to grow only local varieties even though hybrid maize is more profitable in the higher net returns range.

Safety-First Behavior

Flinty local varieties can be more efficiently processed into the fine white flour Malawians prefer to use when preparing their staple dish, and are more resistant to insects in on-farm storage than are denty hybrids. In a culture where the words for maize and food are often used interchangeably, producing sufficient local maize to meet subsistence needs is the foremost goal of most farm households. Farmers who adopt denty hybrids generally produce them for sale. They continue to grow local varieties for home consumption because they cannot rely on markets to deliver local maize—especially in times of serious shortfall. Despite recent market liberalization measures, private markets for local maize remain thin and uncertain, and most of the maize in official markets is hybrid.

Learning

Most farmers have been growing hybrid maize for only a few years and are still learning about cultivating the new seed type on their own fields. Until recently, extension messages have been fairly simple and uniform, with limited adaptation to local conditions. The varieties recommended for a particular agroclimatic regime have not always been available in that zone.

A General Land Allocation Model

The theoretical model proposed here is designed to incorporate each of the four explanations for land allocation to both seed types as a special case. The model depicts a Malawian small farmer who chooses to allocate maize area between a local maize variety that is preferred for home consumption but may be sold in seasons of surplus production, and a higher-yielding hybrid that is consumed in times of duress but usually sold. Although the farmer may be either risk neutral or risk averse, the yields of both the local variety (x) and the hybrid (y) are stochastic. The farmer has sown local maize, with or without fertilizer, for many seasons, and is familiar with corresponding yield distributions. He or she is less familiar with hybrid seed and fertilizer technology. By planting hybrid maize in any period, the farmer has the potential to gain information about fertilized hybrid maize that is valuable in future periods. The farmer chooses land allocations (L_x, L_y) and rates of fertilizer application (z_x, z_y) that maximize expected utility. The farmer faces both a constraint on total maize area (L)[4] and a cash-plus-credit constraint ($W + C$) on production expenditures [$c(\cdot)$].

Net income ($\hat{\pi} = \pi - \rho$) is the value of net returns from maize production (π) less a penalty (ρ) associated with falling below local maize subsistence requirements. The penalty function assigns positive penalties (hidden costs) to combinations of choice and output which are "disastrous." Leathers (1990) has shown how safety-first characterizations can be expressed as special cases of an expected (continuous) utility maximization model in which the argument of the utility function is observable income adjusted by a penalty associated with hidden, or "psychic" costs of disastrous outcomes. The advantage of this formulation is that, although the argument of the utility function is discontinuous, the utility function has properties consistent with classical axioms of consumer choice.[5]

The penalty function (ρ) is positive when production of local maize is insufficient to meet annual household subsistence requirements, and has a value of zero when the farm household produces more than its minimum consumption needs. The penalty is also stochastic, since it is a function of the ratio of local maize output [$X = x(z_x)L_x$] to household requirements ($\bar{X}$). The penalty function is convex because, for any family, the greater the shortfall, the greater the marginal cost of the strategy to be undertaken, or the more severe the reorganization of household resources that is required to close the deficit.

The farmer also gains information about growing maize hybrids by planting at least some area in fertilized hybrid maize and updating his or her information set. The information set I_t is a function of the amount of land allocated to the new variety over all previous time periods ($I_t \mid L_{t-i,y}$; $i = 1, \ldots, \infty$). The expected utility function is conditional on I_t (meaning $\mathrm{E}_t = \mathrm{E}\{[\mathrm{U}(\cdot)] = I_t\}$), and expected future marginal utility is greater in any period whenever the farmer chooses to grow hybrid maize in the current period.

Output prices (p_x, p_y) are nominal observed market prices. Both output prices and fertilizer prices are assumed to be known with certainty in each production period, because they are regulated and announced before planting by the official marketing agency.

In summary, the farmer plans land allocation and fertilizer input decisions $\mathbf{d_t} = [L_{tj}, z_{tj}; j = x, y]$ at the beginning of each season (t), given maize cropping area, credit constraints, and the farmer's subjective beliefs about stochastic returns at harvest time. Nominal costs associated with each input choice $\mathbf{d_t}$ are $\Sigma_j c_j(\mathbf{d_t})$, where c_j are the production costs for varietal choice j. The farmer has the potential to gain valuable information by planting hybrid maize. The farmer also faces hidden, stochastic penalties for choosing land allocations that lead to shortfall outcomes in local maize production. Thus, the farmer's intertemporal problem is

$$\max_{\mathbf{d}_0,\ldots,\mathbf{d}_T} \left\{ \sum_{t=1}^{T} r^{t-1} \mathrm{E}_t U\left[\hat{\pi}(\mathbf{d}_t)\right] : \sum_j L_{tj} \le L_t ; \sum_j c_j(\mathbf{d}_t) \le W_t + C_t \right\}.$$

The problem is solved by backward induction. Viewed from any single period, the decision $\mathbf{d_t}$ satisfies

$$\max_{\mathbf{d}_t} \left\{ \mathrm{E}_t U\left[\hat{\pi}(\mathbf{d}_t)\right] + \sum_{i=t+1}^{T} r^{i-t} \mathrm{E}_i U\left[\hat{\pi}(\mathbf{d}_i^*)\right] : \sum_j L_{tj} \le L_t ; \mathrm{E}_j c_j\left(\mathbf{d}_t\right) \le W_t + C_t \right\}.$$

where $\mathbf{d}_i^*$ represents future optimal decisions. In any production period, the farmer gains utility both from current net income and the discounted future flow of information that results from current adoption decisions.

Each of the four theoretical explanations is a special case of the model. Input fixity is represented by the land constraint ($\Sigma_j L_{tj} \le L_t$) and the cash-plus-credit constraint [$\Sigma_t c(\mathbf{d_t}) \le W_t + C_t$]. Portfolio selection is implied by maximizing the expected utility over the joint distribution of returns from both traditional and new maize types. The penalty function expresses safety-first behavior within the expected utility framework (Leathers 1990). The role of learning is reflected in the effect of past experience on current land allocation.

[4] Malawi's labor-to-land ratio is high by African standards, and in most of the major maize-producing zones, land rather than labor supply constrains farmer choices.

[5] Although other approaches can be used to represent safety-first behavior (e.g., Fafchamps), the penalty function approach is used here because it provides a tractable econometric representation that can be considered simultaneously with other explanations.

The comparative statics of the general model are uninformative because of the ambiguity associated with a large number of direct and indirect effects, and best understood by considering each of the four theoretical explanations in isolation. For each special case, results are already in the literature described above. In the case of input fixity, the utility function is linear, risk does not matter, learning does not occur, and safety is not an issue. Allocation of land to new maize types is then limited only by land, input rationing, or cash-credit constraints, as in various input allocation models derived from the Shumway, Pope, and Nash framework. In the case of portfolio selection, non-land inputs are available at market prices, learning does not occur, and safety is not an issue. Allocation of land to new maize types is determined by a point on the mean-variance frontier that is consistent with risk attitudes, as in the Just and Zilberman results. Similarly, the comparative static implications of other special cases follow from previous work.

Econometric Estimation

In this section, the data source, estimating equations, and estimation procedure are briefly summarized. Data collection methodology and detailed survey statistics are found in Smale et al.

Data

Data are from a survey implemented by the International Maize and Wheat Improvement Center (CIMMYT) and the Malawi Ministry of Agriculture (MOA), in three of the five major maize-producing Agricultural Development Divisions (ADDs) during the 1989–90 cropping season. The sample of 420 farm households was drawn from a stratified cluster frame designed by the National Statistical Office for the Annual Sample Survey of Agriculture (ASA). The adoption data were collected as an extension to the agronomic, crop production, and household income data routinely collected in the ASA.

Estimating Equations

By definition, the maize area constraint in the model holds. The first-order conditions of the theoretical model for the single period case can be written to express (1) the share of maize area planted in hybrid seed (α), (2) the fertilizer application rate for hybrid maize (z_y), and (3) the fertilizer application rate for local maize (z_x) as functions of input and output prices (c, p_y, p_x), cash at planting (W), credit availability (C), parameters and arguments of the utility function, and arguments of the penalty function ($\bar{X}, L$).

Several simplifying assumptions were used to derive estimating equations that provide tractable general and nested models with a single period of cross-sectional data. For brevity, a linear mean-variance approach (Just and Zilberman) is used rather than an explicit form for the utility function. Farmers' objectives can be expressed in terms of their yield expectations (μ_y, μ_x) and perceptions of relative yield variance (σ_y^2, σ_x^2). The mean-variance expressions can also be rewritten in terms of the ratio of perceived yield variances (σ_y^2/σ_x^2).

The expected value of per hectare net returns from maize production (excluding subsistence penalties) is per hectare gross returns less fertilizer costs, or $E\pi = (p_y\mu_y - cz_y)\alpha + (p_x\mu_x - cz_x)(1 - \alpha)$. The constant cost function is the per unit price of nitrogen, the major component of the cash cost of growing hybrid maize in Malawi. The output price ratio (p_y/p_x) is used because, although price differences between maize types can be observed in local markets, the official price is the same for both and price differences reported by farmers for the two maize types were not significant at the mean.

The severity of the subsistence penalty depends on household subsistence requirements ($\bar{X}$) relative to local maize production (X) and is translated into an expected relative impact on land allocation by comparing household requirements to production capacity ($\bar{X}/L$). The subsistence ratio ($\bar{X}/L$) combines the exogenous arguments of the penalty function in one standardized variable.

Input fixity is represented by two variables which determine the cash-plus-credit constraint. Cash available to the household at planting (W) and qualification for credit club membership ($\hat{C}$) are both predetermined for the single-period decision. The variable $\hat{C}$ expresses some of the institutional causes of input fixity. Credit club membership enables Malawian farmers not only to obtain inputs on credit with no transport costs, but guarantees them priority access to rationed seed and fertilizer during shortages. Club membership is strongly associated with chances for growing fertilized maize, and because of fixed-size packages, affects the hybrid area planted and rate of fertilizer applied.

With a single period of cross-section data, gaining information through on-farm learning can be expressed through a variable measuring the farmers' past experience growing hybrid maize (k).[6] In simplest form, adoption history is measured by the number of previous years in which the farmer occupied the adoption state.[7] The variable (k) measures the influence of learning-by-doing on land allocation to maize hybrids, independent of its effect through the revision of yield expectations. The method used to elicit yield expectations (based on farmers' experience) and the similarity of observed and expected yield distributions in the sample (Smale et al.) support this approach.

The general theoretical approach and its special cases have a parallel in the general estimating model and its nested models. When all four theoretical explanations determine adoption decisions, the estimating equations are the reduced-form equations for the single period input choices $d_j = f_j(s)$ where d_j consists of the input choices (α, z_y, z_x) and s is the vector [p_y/p_x, c, μ_y, μ_x, σ_y^2/σ_x^2, $\bar{X}|L$, W, $\hat{C}$, k]. When only one or several of the theoretical explanations hold, the input choices are functions of subsets of the regressors included in the general specification. If, of the four theoretical explanations, only risk aversion matters, the reduced-form equation for the land allocation choice includes prices (p_y/p_x, c), expected yields (μ_y, μ_x), and the ratio of yield variances (σ_y^2/σ_x^2). When the farmer is risk neutral and only learning affects the choice of land allocation to varieties, the reduced-form equation contains only expected yields (μ_y, μ_x), prices (p_y/p_x, c), and the effect on hybrid maize area of learning-by-doing (k). When input fixity alone explains adoption decisions and the farmer is not averse to risk, the reduced-form equations include prices (p_y/p_x, c), expected yields (μ_y, μ_x) and credit and expenditure constraints (W, $\hat{C}$). Finally, when only subsistence (safety-first) penalties explain input choices and the farmer is risk neutral, the reduced-form equations include only the argument of the penalty function ($\bar{X}/L$), prices (p_y/p_x, c),and expected yields (μ_y, μ_x). Estimating equations for combinations of explanations are determined in the same way.

[6] The theoretical section refers to the information set (I). As pointed out by a reviewer, years growing hybrids is a weak but commonly used proxy in empirical work.

[7] Representing experience in this fashion is consistent with a simple Polya process as represented in the Heckman (1981) model, in which occupying the "adoption state" in a previous time period influences the probability of occupying that state in a later period. The stochastic structure of the model is represented by both systematic and random components. In the version of the model that is derived from a Polya process, the history of occupying the "adoption state" is the systematic component.

Table 1. Measured Variables

Endogenous Variables	
α	land area planted to hybrid maize (ha)/total maize area (ha)
z_y	fertilizer application rate, hybrid maize (kg N/ha)
z_x	fertilizer application rate, local maize (kg N/ha)
Exogenous Variables	
p_y	price per kg hybrid maize (MK)
p_x	price per kg local maize (MK)
c	price of N (MK/kg N)
$\mu_y \mid z_y$	(subjective) expected yield for hybrid maize
$\mu_x \mid z_x$	(subjective) expected yield for local maize
$\frac{\sigma_y^2 \mid z_y}{\sigma_x^2 \mid z_x}$	ratio of variances computed from (subjective) yield distributions for hybrid and local maize
$\bar{X}|L$	ratio of estimated family subsistence requirements to total maize area (kg/ha)
W	cash available at planting
$\hat{C}$	qualification for credit club membership
k	total number of years the farmer has grown hybrid maize

MK = Malawi kwacha

Variable Measurement

Empirical measures for the variables defined above are shown in table 1. The share of maize area planted in hybrids is computed from measured areas for hybrids and all maize types. Fertilizer application rates are computed from measured areas and the nitrogen content of the fertilizer type and weight applied. Output prices were elicited from farmers during harvest. Nitrogen price is computed from total fertilizer expenses, fertilizer quantities and type. The variable k is the number of years growing maize hybrids previous to the survey season, as reported by farmers.

Expected yields and perceived yield variances were computed from farmers' subjective yield distributions, elicited as a set of triangular distributions conditional on choice of seed type, with and without fertilizer.[8] For the distributions of fertilized seed types, the implicit rate of application was assumed to be close to the farmer's optimum. Farmers were asked to state the minimum, maximum, and modal output they would expect to obtain from a given plot, with each technique, based on their experience. To compute yield figures, output estimates were divided by the measured area of the plot.

Maize subsistence requirements for the household were computed from the size and age composition of the household, according to annual per capita estimates used by the government of Malawi. The dominance of maize porridge in calories consumed means that there is little variation in the quantity of maize required to meet the minimum caloric needs of a rural person of a given age bracket.

The variable W is defined as the value of maize stocks from last season's harvest that have not been consumed by planting time. Maize stocks were measured at planting and valued with prices reported by farmers. Members of official credit clubs are selected locally based on a combination of subjective considerations, such as villagers' assessment of their standing and character, and objective characteristics, including their land area and collateral such as livestock. Jointly-operated households have been more likely to qualify than female-headed households. The variable $\hat{C}$ is computed as the predicted outcome from the probit regression of actual credit club membership on farm size, sex of household head, regional dummy variables, and two dummy variables for (*a*) ownership of cattle and (*b*) small livestock (pigs, goats, and sheep).[9]

Estimation Procedure

Each set of three estimating equations forms a simultaneous system in which all endogenous variables are censored at zero and no negative values are observed. The package diffusion method used in Malawi, in particular, implies that the seed and fertilizer choices are simultaneous. For each farmer, the disturbance terms for seed and fertilizer choices are also likely to be interrelated.

A suitable econometric technique for testing nested models composed of simultaneous equations with censored variables is Heckman's well-known two-step procedure (1979). In the first stage, a probit equation is estimated for each equation and the inverse Mills ratio is computed from fitted values for each sample observation. In the second step, using only the observations with positive values of the dependent variable, linear equations that include the inverse Mills ratios as regressors are estimated. Second-stage estimators are consistent but not efficient in single equation estimation.

There are two distinct advantages associated with employing the Heckman procedure. First, in the second-stage estimation, the reduced-form equations for the adoption choices can be estimated as an SUR system because only observations with positive values for censored values are included. Information about the relationship between the error terms for the input choices of individual farmers can be included in the estimation procedure. Second, feasible methods for correcting standard errors and estimates of error variances have been developed for the Heckman procedure.

There are three alternatives to the Heckman procedure for estimating simultaneous systems of censored endogenous variables. Maximum likelihood methods are feasible, but become computationally difficult as the number of equations increases. Lee; Maddala and Lee; Nelson and Olsen; and Amemiya also proposed two-stage estimation procedures. For brevity, the approach used by Maddala and Lee, Nelson and Olsen, and summarized in Lee (1981) will be termed NOML. The major disadvantage of the NOML approach is that input choice equations cannot be jointly estimated. In the first stage, reduced-form equations are estimated individually using tobit. In the second stage, fitted values that are computed from the first stage are substituted for endogenous regressors, and structural equations are also estimated invidually using tobit.

Although Amemiya's estimator is, under some conditions, more efficient than the NOML estimator and can be used to estimate an SUR system in the second stage,[10] it has other practical disadvantages. First, the second stage regression in Amemiya's procedure introduces heteroskedasticity. Second, the actual number

[8] In other words, elicited variables are $\mu_y = z_y$, $\mu_x = z_x$, $\sigma_y^2 = z_y$, $\sigma_x^2 = z_x$ for $z_x, z_y >> 0$ and $z_x, z_y = 0$.

[9] Qualification for credit club membership is used because credit club membership is likely to be an endogenous variable in the adoption decision.

[10] Amemiya (1979) proposed OLS and GLS alternatives to the NOML estimator, and has shown that although the NOML and his OLS and GLS estimators are consistent and asymptotically normal, his GLS estimator has a smaller variance-covariance matrix in the case of one censored and one continuous variable. If the structural parameters are estimated with OLS, the relative efficiency of NOML and Amemiya estimators is indeterminate. More generally, Lee (1981) demonstrated that Amemiya's GLS estimator is asympotically more efficient when the dependent variable has probit, censored, or tobit structure. A feasible GLS method has been developed only for a two-equation system.

of observations in the second-stage system can be very small and the number of degrees of freedom is equal to the number of exogenous variables in the system.

To test which single approach or combination of theoretical approaches is most likely to explain land allocation to hybrid maize in Malawi, the general model and each of the fourteen nested models were estimated with the modified Heckman procedure just described. For each model, the first step was to estimate a system of probit equations with the subset of regressors appropriate to that model, defined as above. In the second step, the input choice equations were estimated iteratively as an SUR system, with the same set of regressors and the (fitted) inverse Mills ratio. Using a likelihood ratio test, the values of the log-likelihood functions for the SUR systems were compared between restricted and unrestricted models.

Linearity was imposed on the system to facilitate estimation with the Heckman procedure. The first-stage probit equations must be estimated linearly. The second stage estimation might be adapted for nonlinear least squares but with unknown statistical implications. If the true system is nonlinear, imposing linearity can result in biased estimators. On the other hand, the essential argument of this article involves a comparison of nested models rather than the size and significance of individual parameter estimates. Comparative measures of overall fit within a common estimating structure, rather than magnitudes of estimated coefficients, constitute the relevant statistical evidence.

Results

Second-stage SUR regression results are reported in table 2. For the general adoption model and each of the fourteen nested alternative models, table 2 shows the value of the log-likelihood function for the equation system and asymptotic t-test results. Results for other input choice equations are shown in the appendix. In each of the tests comparing the "General" model to one of the nested alternatives, the null hypothesis was rejected with less than a 4% significance level.[11]

The findings shown in table 2 illustrate the methodological problem that results from advancing single hypotheses to the exclusion of competing alternatives. Likelihood ratio tests suggest that the four theoretical approaches are more likely to jointly explain the land allocation choices of Malawian smallholders than any single approach or combination of two or three approaches. Farmers' land allocation to hybrid maize is affected jointly by their perceptions of expected yields and relative yield variation of the two maize types, their experience with maize hybrids, their cash and credit position, and their maize subsistence needs relative to maize area they farm. To the extent that each explanation is expressed in observable variables, risk aversion, safety-first, learning and input fixity arguments are jointly compatible with the data.

At the same time, testing each explanation to the exclusion of the others produces significance for several individual hypotheses. Table 2 demonstrates the potential for confusion when a researcher assumes a single explanation as the maintained hypothesis and uses t-test results as evidence to statistically "verify" the underlying model. For example, a researcher could advance the hypothesis that portfolio selection explains Malawi farmers' land allocation to hybrid maize, run a regression such as P in table 2, reject the null hypothesis for the t-test on the coefficient of the variance ratio, and conclude that risk aversion matters—to the exclusion of alternative hypotheses that had not been tested. Similarly, another researcher could find statistical support for the safety-first (regression S) or learning(regression L) explanations. The potential for confusion lies in the implicit assumption that if one explanation is correct, the others are incorrect. Because the explanations are not mutually exclusive, a finding that risk aversion may be a factor affecting adoption decisions does not eliminate the possibility that input fixity is also a factor, and vice versa. Further, the significance of an individual explanation may be overstated because the other explanations are not considered. Compare, for example, the significance of the $\overline{X}/L$ coefficient in regression S to the "General" case.

Summary

In the literature on seed-fertilizer innovations in developing countries, any one of several competing theoretical approaches is usually invoked to explain farmers' allocation of land to both new and traditional seed types. Previous

[11] An alternative specification for the land allocation problem is with hectares planted in hybrid maize as the dependent variable and a binding maize area constraint. Applying the same econometric procedure, relative rankings of the general and nested models were the same with either specification. Several individual t-test results are sensitive to specification, however.

Table 2. Econometric Comparison of General Adoption Model with Nested Alternatives (Land Allocation Equation)

Model (Choice variable α)	Explanatory Variables[b]										Value of log-likelihood for SUR system
	p_y / p_x	c	μ_y	μ_x	σ_y^2 / σ_x^2	$\bar{X}/L$	$\hat{C}$	W	k	IMR[a]	
General	0.200**	−0.0575*	0.000000736	−0.0000745**	−0.00289*	−0.0000219	−0.100^{++}	0.000225*	−0.00760^{+}	−0.151^{++}	−942.7978
Portfolio (*P*)	0.179**	−0.387**	0.000109**	−0.000106	−0.00507**					1.21^{+}	−955.7183
Safety–first (*S*)	0.232**	−0.170**	0.0000194	−0.0000935		−0.000231**				−0.592	−954.7406
Input fixity (*F*)	0.216**	−0.0890*	−0.0000256	−0.0000112			−0.0365	0.00043		−0.0414	−956.4058
Learning (*L*)	0.159**	−0.0595*	−0.0000178	−0.0000509*					−0.00820^{+}	−0.136^{++}	−954.5331
P,S,F	0.223**	−0.0739*	−0.00000164	−0.0000453	−0.00264*	−0.0000226	−0.4693	0.000371		−0.0390	−948.9997
P,F,L	0.206**	−0.0524*	0.00000197	−0.0000704**	−0.00293*		−0.106^{++}	0.000947	−0.00720^{+}	−0.136^{++}	−947.5453
S,F,L	0.204**	−0.0681**	−0.0000254	−0.0000358		0.0000180	−0.100^{++}	0.000245*	−0.00734^{+}	−0.149^{++}	−945.8489
P,S,L	0.150*	−0.0565*	0.00000637	−0.0000927**	−0.00287*	0.0000316			−0.00828^{+}	−0.151^{++}	−946.4866
P,S	0.234**	−0.166**	0.0000521*	0.0000613	−0.00315*	−0.00315*				−0.644	−951.8049
P,F	0.214**	−0.0763	−0.00000140	−0.0000485	−0.00273*		−0.0434	0.000391		−0.032	−953.3519
P,L	0.158**	−0.0496	−0.00000715	−0.0000874**	−0.00283*				−0.00854^{+}	−0.134^{++}	−951.2911
S,F	0.227**	−0.0843*	−0.0000252	−0.00000989		−0.0000268	−0.0445	0.000394		−0.0429	−951.6672
S,L	0.153**	−0.0665*	−0.0000192	−0.0000552*		−0.000028			−0.00803^{+}	−0.152^{++}	−948.9099
F,L	0.208**	−0.0637*	−0.0000244	−0.0000315			−0.105^{++}	0.000234*	−0.00690	−0.134^{++}	−951.0366

** significant at 0.05, one–tailed
* significant at 0.10, one–tailed
$^{++}$ significant at 0.05, two–tailed
$^{+}$ significant at 0.10, two–tailed
[a] fitted value of inverse Mills ratio
[b] standard errors are available on request

survey research in Malawi provides evidence that, in that context, any one or several competing approaches may explain land allocation in adoption decisions. The model employed in this paper is designed to incorporate portfolio, safety-first, experimentation and input fixity arguments as special cases of a general problem.

Given the assumptions used to facilitate econometric estimation and the procedure employed, the statistical results are consistent with the notion that no single theoretical argument, in and of itself, fully explains the land allocation decisions of hybrid maize adopters in Malawi. The general model containing all four explanations is more likely to explain land allocation patterns than any single approach or combination of two or three approaches.

The major implication of this result is the need to recognize the importance of competing hypotheses in the applied study of technology adoption. For example, although a combination of factors that are both related and unrelated to farmer risk attitudes may explain technology choices, researchers applying conventional risk models may incorrectly conclude that risk aversion alone (or some other sole explanation) is the determining factor.

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Appendix

Additional Econometric Results for Fertilizer Equations

Model and Choice Variable		Explanatory Variables[b]									
		p_y / p_x	c	μ_y	μ_x	σ_y^2 / σ_x^2	$\bar{X}/L$	$\hat{C}$	W	k	IMR[a]
General	z_y	49.6***	–2.51	–0.0106	0.0141++	0.409+	0.0112++	–3.01	0.0290	1.02	7.47
	z_x	5.78	–25.24**	0.00802	–0.00302	0.351	0.00211	3.41	0.00707	–1.78	–24.0
Portfolio (P)	z_y	51.5***	–21.9	–0.00150	0.0180+	0.608					62.9
	z_x	–151.8	357.19	–0.344	0.429*	11.89					–539.0
Safety–first (S)	z_y	47.9***	–8.36	–0.00307	0.0142		–0.00278				34.9
	z_x	–11.1	3.37	–0.0048	–0.0069		0.0442				–535.0
Input Fixity (F)	z_y	53.2***	–7.61	–0.00497	0.0108+			10.5	0.0710		28.7
	z_x	11.1	38.8**	0.0158++	–0.0239			79.5	0.282		273.0
Learning (L)	z_y	52.5***	–0.177	–0.00651	–0.00766					1.02	9.3
	z_x	6.7	–23.2**	0.0116++	–0.00771					–1.89	–26.3
P,S,F	z_y	49.1***	–6.56	–0.00882	0.0152++	0.351	0.00725	5.21	0.0631		18.9
	z_x	10.9	–34.0**	0.0185+	–0.0274	0.0787	–0.00791	71.5	0.254		265.0
P,F,L	z_y	55.7***	–2.13	–0.0111	0.0150++	0.479		–4.34	0.0180	1.08	10.4
	z_x	6.75	–24.9**	0.00794	–0.0293	0.360		2.91	0.00489	–1.73	–22.6
S,F,L	z_y	48.9***	–9.12	–0.00698	0.00861		0.0120++	–3.20	0.0264	0.948	6.67
	z_x	5.06	–23.9**	0.0115**	–0.00805		0.00265	3.20	0.446	–1.92	–26.2
P,S,L	z_y	46.2***	–1.81	0.00972	0.0125+	0.383	0.0112++			1.22	7.07
	z_x	6.63	–24.8**	0.00817	–0.00276	0.351	0.0113			–1.71	–25.4
P,S	z_y	49.3***	–12.0	–0.00308	0.0179+	0.145	–0.00843				46.9
	z_x	–23.2	12.3	–0.0534	0.0567	2.28	0.0775				–100.4
P,F	z_y	53.2***	–10.6	–0.00788	0.0158++	0.369		13.3	0.0828		33.4
	z_x	10.1	–37.3**	0.0188	–0.302	0.690		77.4	0.275		269.0
P,L	z_y	52.8***	–1.93	–0.00137	0.1366+	0.458				1.12	9.7
	z_x	7.0	–24.5**	0.00812	–0.00264	0.355				–1.72	–24.6
S,F	z_y	48.4***	–3.90	–0.00614	0.00999		0.00941	2.62	0.0529		13.4
	z_x	11.7	–34.9**	0.0157++	–0.0211		–0.00828	72.3	0.258		265.5
S,L	z_y	45.6***	–0.412	–0.00635	0.00747		0.0119++			–1.14	–6.59
	z_x	6.08	–23.5**	0.0116++	–0.00779		0.001755			–1.87	–27.4
F,L	z_y	55.2***	–0.11	–0.00685	0.00864			–4.79	0.0157	0.991	9.38
	z_x	6.25	–23.4**	0.0115+	–0.00804			2.55	–0.00164	–1.87	–24.7

*** significant at 0.01, one–tailed
** significant at 0.05, one–tailed
* significant at 0.10, one–tailed
[a] fitted value of inverse Mills ratio
[b] standard errors are available on request

+++ significant at 0.01, two–tailed
++ significant at 0.05, two–tailed
+ significant at 0.10, two–tailed