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Modeling the impact of technological change on nutrition and marketed surplus

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Abstract

This study develops and demonstrates procedures for modeling the impact of agricultural technology adoption decisions on consumption and nutrition in a subsistence-farming context. The method is based on expected direct utility maximization (EDUM) formulation and incorporates subsistence quantities for broad aggregates of protein, calories, and other consumption goods. The method is applied to a hillside farming system of southern Honduras where new sorghum cultivars and erosion control techniques are being introduced.

The expected direct utility maximization model allows the estimation of the effects of new technology on consumption and marketed surplus in situations where marginal values of products vary by state of nature and are affected by consumption and production choices. The introduction of the new technologies in southern Honduras results in improved nutrition and substantial increases in marketed surplus. These effects are due to simultaneous changes in output and consumption patterns. This work extends the subject of household modeling to problems with risk, and thus complements prior work in both the integrated analysis of production/consumption decisions and stochastic decision analysis.

Keywords: Direct utility maximization; Indirect utility; New technology; Nutrition

1. Introduction

Technical change leads to increased output by poor farming households, and higher disposable income. The direct food consumption effect of increased productivity and high income is an increase in the level of food consumption and improved nutrition, and consequently, a reduction in food insecurity, of the adopting household. Besides increased household consumption from own-production, higher cash income from new technology is also associated with increased expenditure on purchases of basic food staples as well as fruits, vegetables and other high value products. Substitution of cheap calories from staples for more expensive calories, especially livestock products such as milk and meat, often takes place and diets gain in quality and diversity.

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Whole-farm mathematical programming is often used to model the impact of new technology on subsistence farms. The common modeling approach assumes that the farm household maximizes its expected utility of wealth subject to a set of resource constraints and minimum consumption levels. This approach is not well suited for the prediction of nutritional effects and changes in consumption levels or substitution among consumption goods and, consequently, overestimates the impact of the new technology on marketed surplus. This information is especially important for policymakers forecasting the availability of food grains for urban consumers and planning food grain imports and exports.

In this article, an expected *direct-utility* maximization (EDUM) approach is used to model subsistence household production and consumption decisions and the impact of new technology introduction on crop mix, consumption and nutrition. Although a wide spectrum of nutrients is necessary for healthy human development, protein and energy are particularly emphasized here. This emphasis is chosen because of the current consensus among nutritionists that energy and protein malnutrition is the major nutritional problems in developing countries (Meller and Johnston, 1984; p. 547). In this study, new technology is introduced in the model by allowing a wide choice of alternatives. These include two new sorghum cultivars, Sureño and Catracho, and soil erosion control of the hillside lands in southern Honduras combined with chemical fertilizer and insecticide.

The next section of this paper derives the relationship between the direct and the indirect utility models under uncertainty. In the third section, the empirical model and data are described. The results of the two models are contrasted in section four, and conclusions and implications are drawn in the final section.

2. The direct and indirect utility maximization models

In a problem involving allocation of resources under uncertainty, it is customary to deal with utility functions for aggregate consumption, namely, a utility function whose sole argument is the dollar value of consumption. This approach is described here as *indirect* because utility is a function only of wealth. A more *direct* approach accounts for the fact that the individual's desire for income ultimately derives from his utility for consumption goods (Fama and Miller, 1972; p. 206).

The conventional view of decision making under uncertainty is that choices can be modeled as expected utility maximizing, provided the decisionmaker's preferences satisfy the axioms of the expected utility model (Fama and Miller, 1972; p. 206; Fama, 1972, p. 127). However, to express utility as a function of wealth, other features of the indirect utility formulation would also have to hold. Namely, prices of consumption goods must be unaffected by consumption choices. (As will be seen in the empirical section, the independence of marginal values — internal prices or opportunity costs at the household level — and consumption may be violated if there are wedges between buying and selling prices of goods that are produced by the household). If the utility of consumption, $U(C)$, is monotonically increasing and concave in the vector of consumption quantities, C, then the indirect utility function, $V(w,P)$, is monotonically increasing and concave in wealth, w, implying risk averse behavior in the presence of uncertainty regarding w.

The linear expenditure system (LES) reasonably approximates consumption decisions of subsistence farmers in developing countries where satisfying subsistence levels for food is an important objective. The LES implies that consumer preferences can be represented by the Stone–Geary utility function:

$$u(C) = \prod_{i}^{n} (C_i - \gamma_i)^{\beta_i} \tag{1}$$

where γ_i is interpreted as the subsistence level of good i, and β_i is the nonnegative share of the discretionary budget expended upon that good. This utility function exhibits decreasing marginal utility of all goods (above the subsistence level). Inferior goods are excluded since all income elasticities are positive. This could be considered as a reasonable restriction only if the model is implemented for broad consumption aggregates (Phlips, 1983, p. 128). That is, subsistence levels might be defined for an aggregate measure of a group of goods that provide some basic nutrient (e.g. a minimum requirement of protein might be satisfied by consumption of meat and beans, or a subsistence level of calories might be satisfied by consumption of one or more cereals.). Similarly, consumption goods in each group could be nested in such a way as to express the supply of that basic nutrient. Consider the following form of utility of consumption:

$$V(w,p)=\max_{C_{ij}} u(C)$$
$$=\left(\frac{1}{1-\rho}\right)\left(\prod_{i=1}^{k}\left(A_i\prod_{j=1}^{n_i}C_{ij}^{\alpha_{ij}}-\gamma_i\right)^{\beta_i}\right)^{1-\rho}$$
$$\text{subject to}: \sum_{i=1}^{k}\sum_{j=1}^{n_j}p_{ij}C_{ij}\le w \quad C_{ij}\ge 0 \quad (2)$$

where $u(C)=u(C_{11},C_{12},\ldots C_{1n_1}, C_{21},\ldots, C_{kn_k})$ is the direct utility of consumption, A_i a scaling parameter that equalizes the units of the product and the units of the subsistence quantity, k the number of consumption/nutritional classes (e.g. protein, calories and nonfood), n_i the number of commodities within the consumption good class i, C_{ij} the consumption level of the jth good in the ith consumption good class, γ_i the minimum (subsistence) level for the ith class of consumption goods, ρ a risk aversion parameter, and, α_{ij}, β_i are the nonnegative parameters such that $\sum_{i=1}^{k}\beta_i=1$, and $\sum_{j=1}^{n_k}\alpha_{ij}=1$ for all i.

The risk parameter, ρ, in Eq. (2) above is not the familiar Arrow–Pratt coefficient of relative risk aversion. The latter is limited to the class of problems where utility is a function of a single argument, such as the indirect von Neumann–Morgenstern utility of wealth (Kihlstrom and Mirman, 1974, p. 361; Kihlstrom and Mirman, 1981, p. 271; Duncan, 1977, p. 895). An important aspect of the general class of direct utility functions, from which Eq. (2) is a representative, is that it reflects multivariate risk aversion. A decisionmaker whose utility function can be represented by $u(x,y)$ is said to be a multivariate risk averse (MRA) if and only if for all (x,y) in the consumption set, $u_{xy}(x,y)=(\partial u(x,y))/(\partial x\partial y)\le 0$ (Richard, 1975; p. 14). Multivariate risk aversion can readily be confirmed for the nested Stone–Geary/Cobb–Douglas form in general. As such, the risk parameter can be varied to reflect alternative levels of multivariate risk aversion.

It can be shown that maximization of Eq. (2) above subject to the usual budget constraint yields the following form of the indirect utility of income:

$$V(w,p)$$
$$=\left(\frac{1}{1-\rho}\right)\left[\prod_{i=1}^{k}\left(A_i\beta_i\prod_{j=1}^{n_i}\left(\frac{\alpha_{ij}}{P_{ij}}\right)\right.\right.$$
$$\left.\left.\times\left(w-\sum_{i=1}^{k}\left(\frac{\gamma_i}{A_i\prod_{j=1}^{n_i}(\alpha_{ij}/P_{ij})^{\alpha_{ij}}}\right)\right)\right)^{\beta_i}\right]^{(1-\rho)}$$
$$=\frac{\delta}{1-\rho}(w-\phi)^{1-\rho} \quad (3)$$

where $\delta=[\Pi_{i=1}^{k}\beta_i A_i \Pi_{j=1}^{n_i}(\alpha_{ij}/P_{ij})^{\alpha_{ij}}]^{1-\rho}$ is a constant if prices are constant and ϕ the minimum expenditure level necessary to satisfy subsistence requirements. If prices are assumed to be unaffected by consumption decisions and certain, then all terms other than income in Eq. (3) are constant. Thus, Eq. (3) reduces to the familiar indirect power utility function expressed as a function of the discretionary wealth. If prices are not known a priori and may be affected by consumption choices, or if the budget level is not known before any consumption decisions are made, then utility cannot be stated simply as a function of income, and the direct utility formulation is needed.

In this study, farm-level adoption of new technology is evaluated using the direct and indirect utility models. For the results to be comparable, Eq. (2) is used as the basis for the objective function in the empirical direct utility model, and Eq. (3) is used as the objective function for the empirical, expected indirect utility model derived from it. The empirical models and data required for implementing the two models are described below.

3. Empirical model and data

Discrete stochastic programming, or DSP (Cocks, 1968; Rae, 1971), is used in this study to provide a simultaneous focus on technology adoption and consumption behavior under uncertainty. The empirical models are adaptations of a two-stage DSP model developed by Lopez-Pereira (1990) to estimate the potential impacts of new sorghum cultivars, Sureño and Catracho, and soil erosion control of the hillside lands combined with chemical fertilizer and insecticide on income and productivity of small farmers in southern Honduras. A third stage was added for this study so that the modified models cover a full year. Thus, in both models the planning horizon consists of three stages. Yields and market prices are treated as correlated random variables. The data used in these models is obtained from a household survey in the area (details may be found in Lopez-Pereira, 1990).

3.1. Objective functions

The direct utility model assumes that the household maximizes the expected value of the product of direct utility of consumption in each of the three periods raised to a power equal to the fraction of the year in each period (i.e. let $u_t(C^t)$ be the utility of C^t, where C^t is the sub-vector of C representing consumption in period t, and $u_t(\cdot)$ has the form of Eq. (2). Let δ_t denote the fraction of the year of each period (t=1,2,3). Then the utility function is given by $u(C) = \prod_t^3[u_t(C^t)]^{\delta_t}$). Thus, the objective function is defined as a Cobb–Douglas function of period-wise utility as described by Manne and Preckel (1985). The effect of this choice is to push the consumption bundles toward equality of daily consumption across periods, provided that prices are constant and expenditures may be freely shifted through time.

The period-wise utility function, has the form:

$$u_t(C_t) = \prod_{i=1}^{k}\left(A_i \prod_{j=1}^{m_i} C_{ijt}^{\alpha_j} - \gamma_{it}\right)^{\beta_i} \qquad (4)$$

and is defined over three (k=3) expenditure/nutritional aggregates (nests): calories, protein and cash consumption. The caloric aggregate consists of the staple grains, maize, sorghum, and rice, and the protein aggregate consists of beans and meat. [3] The cash aggregate consists of a single commodity, nonfood, which is expressed as the monetary value of goods other than calorie and protein sources. Thus in Eq. (2), k is equal to three (calorie, protein, and nonfood). These individual consumption goods provide calories (from maize, sorghum, and rice), protein (from meat and beans), and nonfood (with cash serving as the proxy for all 'nonfood' expenditures which also include food items other than cereals, meat and beans, e.g. vegetables, clothing, medical supplies and services, and school expenses).

Households choose production plans so as to maximize the expected utility of consumption. In doing so, the household allocates its available resources including farm land, labor, and cash to the production of maize, sorghum, beans, and chickens, given knowledge of potential yield and price outcomes (hereafter referred to as states of nature). Simultaneously, the household uses its farm output, carry-over inventories of goods, and cash to satisfy its consumption requirements directly through on-farm consumption or indirectly through market exchange.

The implementation of the expected direct utility model requires the estimation of the expenditure shares of consumption goods within each consumption group, the α_{ij}s, and the expenditure shares of each group, the β_is. These expenditure shares were estimated based on average expenditures and prices of the consumption goods reported by Lopez-Pereira (1990). The expenditure shares for calories, protein, and nonfood are 0.253, 0.615, and 0.132, respectively. The expenditure shares of the major sources of energy are 0.639 for maize, 0.197 for sorghum, and 0.164 for rice. The expenditure shares of the major sources of proteins are 0.613 for beans and 0.387 for meat.

The minimum subsistence levels for protein and calories were derived from the accepted minimum standards of adequacy for Honduras of 2138 calories and 45 g of protein per adult per day (Garcia et al., 1987). The minimum standards are converted to a household basis by multiplying by the average number of adult equivalents of 5.7 per household (Lopez-Pereira, 1990). The number of the calories supplied by the consumption of protein sources and the amount of protein supplied by consumption of cereals are calculated from the observed quantities of goods consumed by the average household in Honduras. These quantities were then subtracted from the minimum standards. The resulting minimum subsistence level for calories is 1821 kcal, and that for protein is zero because the quantities of cereals consumed by the average household (specially sorghum

[3] As a reviewer of this journal noted, there can be significant interactions between consumption goods in determining nutrient intake such as that between corn and beans. While this type of complementarity is important and it could be incorporated in our framework, determining the most appropriate nesting from a nutritional perspective is beyond the scope of this paper.

and maize) supply more than the minimum standards of protein. These subsistence levels are adjusted by the number of days per period to obtain a subsistence level of calories for the period, γ_{it}.

The structure of the direct utility model requires that the Cobb–Douglas term for the ith aggregate (i.e. calorie, protein, or nonfood), $A_i\prod_{j=1}^{n_i} C_{ij}^{\alpha_{ij}}$, must exceed the minimum level, (γ_{it}). Placing slightly positive lower bounds on individual C_{ij} ensures that the protein and nonfood consumption aggregates exceed the minimum subsistence levels because those subsistence levels are zero. However, ensuring that the calorie aggregate exceeds its subsistence level without distorting the consumption of any cereal is more difficult. To achieve this goal, bounds on consumption of each good that ensure that the calorie aggregate (the Cobb–Douglas term) will strictly exceed the subsistence level (γ_{it}) in every period may be imposed. Unfortunately, these bounds may be active in some cases, and in those cases, the solution will be distorted by the bounds. The iterative procedure used to obtain a solution where all of the lower bounds on consumption are inactive while ensuring that the calorie aggregate always strictly exceeds the subsistence levels is documented in the Appendix A. The lower bounds on the individual consumption levels (C_{ij}) are dependent on the state of nature, and since they are not binding in the optimal solution, all optimal substitution possibilities are permitted in the satisfaction of the subsistence levels.

In the indirect utility model, the objective of the household is to maximize the expected value of the indirect utility of discretionary wealth (i.e. wealth in excess of the amount required to buy a subsistence consumption bundle). The form for utility is chosen to be similar to Eq. (3) in order to make the results comparable with the expected direct utility formulation. This utility function is equivalent to the power utility function, which has the desirable property of constant relative risk aversion. Mathematically, utility for the indirect case is specified as $u(I)=I^{1-\rho}/(1-\rho)$ where I denotes the value of holdings at the end of the third stage net of subsistence requirements.

3.2. Model activities

As stated above, the modified DSP model consists of three stages corresponding to the farming seasons. The household's decision problem is to select cropping plans for both the first and second seasons with the objective of maximizing the expected utility of household consumption over the three stages. The time line and sequence of decisions and schedule of realization of random events are displayed in Fig. 1.

The selection of farming activities (area allocated to various crops in the first and second stages and commitment to raise chickens) determines the monthly allocation of labor to planting, weeding, harvesting and chicken raising. The first stage starts early in May at the onset of the rainy season. In this stage, the farmer can allocate land to maize, beans, maicillo (a local variety of sorghum), and maize/maicillo. (Maize/maicillo denotes an intercrop of maize and maicillo.) Maize and beans are planted in early May, and maicillo is planted in late May. Beans are harvested in late July and maize is harvested in early August during a marked, short, dry period in the middle of the rainy season. Maicillo is a late-maturing variety that is usually harvested in December during the second season. For the maize/maicillo intercrop, the maize is harvested in the first stage, and the maicillo is harvested during the second stage.

The second stage starts in mid-August, when maize and bean monocrops are planted. The second stage bean crop is harvested in late November while second stage maize is harvested in mid-December. The improved sorghum varieties, suitable for monocropping in both stages, are early-maturing varieties that require about 100 days from planting to harvest.

The third stage extends from February to April and represents the season when there are no cropping activities. Throughout the year, farmers in the region raise farm animals. However, only chicken production is included in the model, due to a lack of reliable data on the production of other livestock.

Therefore, decision variables include crop mix and technology for the first and second stages (cropping seasons), land renting, borrowing, monthly labor hiring in and out, purchases and sales of consumption goods, and quantities of consumption goods, and inventories including cash. It is to be noted that with the discrete stochastic programming approach, the area allocations and consumption in the second growing season are conditional upon the state of nature in the first season. In other words, the area allocations to each crop in the second season and consumption

Time	Decisions	Random events realized
First season planting time (mid-May)	Consumption through first season harvest Land and labor allocation for first season and the two season crop (maize/maicillo intercrop)	
First season harvest time (August)	Marketing and inventory choices for first season crops	Yields and prices for crops harvested at the end of the first season
Second season planting time (August)	Consumption through second season harvest Land and labor allocation for second season crops	
Second season harvest time (December)	Consumption through April of the next year Marketing and inventory choices for second season crops	Yields and prices for crops harvested at the end of the second season are realized

Fig. 1. Time line, decisions and random events for the empirical model.

during the period between second season planting and harvest are a function of the yields and prices realized in the first season. Similarly, consumption during the period between second season harvest and planting for the next year is conditional on the realized yields and prices for both the first and second seasons. Farm production of maize, sorghum, beans, and chicken meat, augmented by inventories, is allocated between consumption quantities in each stage, sales (or purchases), and end of the year inventories. Income obtained from sale of farm production and other sources, e.g. remittances, is used for purchases of rice, and nonfood. Additional quantities of maize, sorghum, beans and meat can be purchased to close consumption gaps in states of nature where own farm production is insufficient.

Production technology is assumed to have fixed input–output coefficients. Production inputs include labor for planting, weeding, and harvesting, seeds and fertilizer. Farm production of maize, sorghum and beans depends on the acreage allocation decisions and the prevailing states of nature since the yields of these crops are random variables and, therefore, not known with certainty at planting time. The probability distribution of yields of all crops, including the new cultivars, is obtained from experimental and on-farm trial results in the southern Honduras. Input use per unit of crop activity is obtained from the household survey (see Lopez-Pereira, 1990).

In addition to production activities, the model contains monthly labor hiring, commodity consumption, purchases and sales, land renting, borrowing, and inventory transfer activities in the first and second stages. The model activities in the third stage include consumption, grain purchases and sales, and inventory carry-over. In all stages, the decision maker is permitted to buy chickens to raise for consumption but not for resale.

The farmer begins the new cropping season with an initial inventory of 200 kg of maize, 250 kg of sorghum, 35 kg of beans, 15 chickens, and the equivalent of US $70 in cash from the previous year. This inventory of grains and beans may be used for consumption or can be sold to cover cash expenses of production and for the purchases of other goods. The farmer is also required to have a year end inventory that varies by state of nature in proportion to yield of the major crop, maize, and that, on average, equals beginning inventory.

3.3. Model constraints

For the first and second stages, the empirical model consists of land constraints for each stage, labor constraints for planting, weeding and harvesting, and inventory balances for grains, cash, beans, and animals. Only inventory balance constraints appear in the third stage. The available land constraint was based on the average farm area of 1.7 ha. Available land can be augmented through renting. Excess family labor can be hired out for off-farm work, and hiring in is permitted.

The inventory constraints at the beginning of each stage account for the inflow and outflow of grains (sorghum and maize), beans, purchased goods (rice and meats), farm animals (chickens), and cash. The sources of cash in this model include sales of grain and beans, off-farm work, borrowing, and remittances from family members living off the farm. Cash is used to pay for input purchases, land rental, purchases of consumption goods, hired labor, animal purchases, and repayment of credit. Grain and bean inventory constraints equate the sum of quantities transferred from the previous season, produced on the farm and purchased to the quantity consumed, sold, fed to chickens, and carried over as inventory.

In the expected direct utility model, total consumption of food is limited to 25% more than the observed amount consumed by the average household in the area. This limits the total quantity of food consumed in states of nature when an extremely good harvest results and market price collapses. The indirect utility model employs minimum consumption constraints based on monthly subsistence requirements for an average family of 5.7 adult male equivalents of 58 kg of maize, 25 kg of sorghum, 9 kg of rice, and 16 kg of beans. Due to the substantial amount of protein in grains, the subsistence level for meat is set to zero.

Random variables in the model are the yields of maize, sorghum, and beans. In the base model without new technologies, the first stage has eight states of nature and the second has 16 states. This produces 128 terminal states in the third season. When the new technologies are introduced, more cropping activities are included. In the resulting expanded model, the Gaussian quadrature method for multivariate normal random variables, as described by Preckel and DeVuyst (1992), was employed to generate a discrete approximation to the yield distribution for use in the DSP model. The new technology model consists of 10 states of nature in the first stage and 12 in the second with 120 terminal states in the third stage. In all models, prices are treated as deterministic functions of the random yield variables determined via regression. Details are found in Lopez-Pereira et al. (1994).

The direct and indirect utility models with and without the new technologies were solved using GAMS/MINOS (Brooke et al., 1992). Two levels of risk aversion were simulated by varying the risk parameter in both models. Because the objective function is highly nonlinear, solution of the EDUM requires twice the computer time required to solve the EIUM. However, once the first model, e.g. the base technology model, is solved, saving the work files created by GAMS for restarting other models saves substantial computer time.

4. Impact of technology on consumption and production plans

Technology affects the resource allocations by changing the potential yield outcomes. From the perspective of the household decisions regarding consumption during the first model period, these changes in yield outcomes affect future marginal values of consumption goods. These affect current consumption decisions by changing the incentive to store goods for future periods. The household will increase current consumption by decreasing storage until the marginal value of consumption in the present and future are equilibrated. The consumption increase will typically be biased towards goods with higher marginal utility. If this utility function has been calibrated to reflect the nutritional goals of the household, then improved technology will have a direct impact on improving nutritional status.

5. Results and discussion

The EIUM and the EDUM were used to examine two scenarios: base case and new technologies. Two levels of risk aversion were considered: ρ=0 and ρ=3 (It is noteworthy that ρ=0 corresponds to risk neutrality in the EIUM case, but not for EDUM. In both cases, increases in ρ correspond to increases in risk aversion.). The results of the two modelling approaches are compared below with focus on crop mix, output, and income. In addition, the impact of the new technology on consumption behavior and marketed surplus, predicted by the EDUM, is presented.

5.1. Base technology results

The results of the base models are useful for determining the impact of new technology on farm income, cropping plan, consumption, and marketed surplus. They are also useful for validating both models by comparing the cropping plan predicted by each to the actual cropping plans observed on farmers' fields. However, this is the extent of validation possible given the limited availability of observed data and that the model embodies several unverifiable assumptions such as the exact form of the utility function of the decision maker, and the level of risk aversion. Thus, the validation here should be interpreted as a test of consistency of the model predictions with the field observation.

The results of the *direct utility model* with base technology show that, with risk neutrality, a total crop area of 1.99 ha is allocated between maize and maize/maicillo intercrop. The majority, 1.42 ha, is allocated to the intercrop activity (Table 1). This amounts to 71% of total crop area. No land is allocated to either monocrop beans or sorghum. The large proportion of land in the intercrop activity is consistent with a farm survey which indicates that 52% of the crop area is allocated to this activity (Lopez-Pereira, 1990). Beans and sorghum were grown by the survey farmers in small proportions, 4 and 11%, respectively. However, beans and sorghum are inferior cropping choices in the modeling results. Beans are costly to produce and are relatively labor-intensive. The model allocates 0.71 ha to sorghum and 1.28 ha to maize in total using both sole cropping and intercropping. This is reasonably consistent with the survey data in which farmers allocated 0.81 ha to sorghum and 1.30 ha to maize. Thus, with the exception of the failure to include the small area of beans, the model results appear to be fairly consistent with observed farmer behavior.

The total crop land available for planting in the second stage is reduced markedly by the large area in the intercrop which spans both growing seasons. The majority of the second season planted area (87%) is allocated on average to maize with only 13% for beans. This compares favorably to the survey results of 80 and 20% in maize and beans, respectively.

Risk aversion has a substantial effect on the crop plan. With high risk aversion, the area in maize doubled while the area in the intercropping activity was reduced substantially, relative to the low risk aversion case (Table 1). This is because the expected value of maize yields in the monocrop is higher and more stable than the value of maize/beans intercrop with relatively low beans yields.

The *indirect utility model* produced similar results with one exception. The crop plan for the indirect utility model is relatively insensitive to increased risk aversion (Table 1). In both models, the farmer used less than all of the land that was available in the first season (1.7 ha of owned land and 1 ha of rented land). In the second season, most of the land was occupied by first season maize/sorghum intercrop, and the farmer rented all of the available land to plant maize and beans. Less than all of the available land was used in the first season due to binding labor and working capital constraints. In the second season, all available land, including rental land, was used. Limits to area farmed due to shortages of working capital and labor were also observed in the survey data (Lopez-Pereira, 1990).

5.2. Adoption of new technology

The New Technology scenario permits allocation of crop land to two new, early-maturing varieties of sorghum, Sureño and Catracho. The expected direct utility model (EDUM) with the lower level of risk aversion under this scenario, suggests that the farmer's activities should change substantially. The farmer allocates significant area to Catracho, eliminates the allocation of land to the maize monocrop, and reduces the allocation of land to the maize/maicillo intercrop during the first season. Due to the greater labor requirements of the new varieties, essentially no land is rented during the first season. During the second season, the small average allocation of land to beans that occurs in the base case is eliminated, and the average allocation to maize is reduced. The allocations to Sureño and Catracho are significant at average values of 0.83 and 0.58 ha, respectively. Second season land rental is reduced on average to 88% of the base case value (Table 1).

Table 1
Crop allocation and income statistics for base and new technologies

Crop activity		Small farm[a]	Base technology				New technology			
			Direct utility		Indirect utility		Direct utility		Indirect utility	
			$\rho^b=0$	$\rho=3$	$\rho=0$	$\rho=3$	$\rho=0$	$\rho=3$	$\rho=0$	$\rho=3$
First season										
Maize		0.73	0.57	1.16	0.57	0.62	0.00	0.23	0.00	0.00
Beans		0.09	0.00	0.00	0.00	0.00	0.00	0.42	0.00	0.00
Maize/Maicillo		1.14	1.42	0.79	1.42	1.37	0.84	0.91	1.12	0.83
Sorghum		0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sureño		N/A	N/A	N/A	N/A	N/A	0.00	0.00	0.00	0.00
Catracho		N/A	N/A	N/A	N/A	N/A	0.88	0.29	0.60	0.88
Total area		2.20	1.99	1.94	1.99	1.99	1.71	1.86	1.72	1.71
Rented area		0.50	0.29	0.24	0.29	0.29	0.01	0.16	0.02	0.01
Second season[c]										
Maize	Minimum		0.03	0.53	0.00	0.00	0.00	0.57	0.00	0.00
	Average	1.25	1.12	0.68	1.12	1.17	0.33	0.78	0.10	0.10
	Maximum		1.28	0.74	1.28	1.33	1.64	1.18	1.58	1.64
Beans	Minimum		0.00	0.61	0.00	0.00	0.00	0.29	0.00	0.00
	Average	0.31	0.16	0.81	0.16	0.17	0.00	0.55	0.00	0.00
	Maximum		1.25	1.03	1.20	1.33	0.00	0.92	0.00	0.00
Sureño	Minimum		N/A	N/A	N/A	N/A	0.00	0.00	0.00	0.00
	Average	N/A	N/A	N/A	N/A	N/A	0.83	0.21	0.00	1.07
	Maximum		N/A	N/A	N/A	N/A	1.25	0.59	0.00	1.05
Catracho	Minimum		N/A	N/A	N/A	N/A	0.00	0.00	0.00	0.00
	Average	N/A	N/A	N/A	N/A	N/A	0.58	0.09	1.48	0.66
	Maximum		N/A	N/A	N/A	N/A	0.97	0.32	1.58	1.05
Total area	Minimum		1.28	1.30	1.28	1.33	1.51	1.40	1.58	1.64
	Average	1.56	1.28	1.49	1.28	1.33	1.74	1.63	1.58	1.83
	Maximum		1.28	1.68	1.28	1.33	1.87	1.72	1.58	1.87
Rented area	Minimum		1.00	0.39	1.00	1.00	0.64	0.61	1.00	0.77
	Average	1.00	1.00	0.58	1.00	1.00	0.88	0.84	1.00	0.96
	Maximum		1.00	0.77	1.00	1.00	1.00	0.93	1.00	1.00
Income[d]	Average		937.9	880.9	922.5	921.9	1157.7	1018.5	1201.1	1137.3
	Standard deviation	N/A	137.9	66.9	156.2	141.6	201.3	120.1	258.1	213.5
	Skewness		526288	−138985	718455	449915	6337125	−864506	8854349	820437

[a] Average crop area in the survey results (Lopez-Pereira, 1990).
[b] Coefficient of relative risk aversion.
[c] Second and third stage decisions are conditional on the yield outcome in stage one and, hence, have distribution. The means, minimum and maximum are reported in this table.
[d] Income defined as the value of consumption of all goods.

With the higher level of risk aversion (and the expected direct utility model), the model predicts that farmers should diversify during the first season by making a significant allocation of area to beans (23%). The first season allocation to maize should also increase to 37%, while the first season allocation to the new variety, Catracho, should decrease to about one-third of the level allocated for the less risk averse farmer. In the second season, the average allocations to maize and beans increase while the allocations to the new varieties decrease substantially relative to the less risk averse farmer, reflecting the high level of risk associated with the new varieties. Area rented is not affected much by the change in risk aversion.

Using expected indirect utility (EIUM) with the lower level of risk aversion under this scenario, the model suggests that the farmer's activities should change substantially relative to the analogous base case model. In the first season, monocrop maize should be replaced in the crop mix by the new variety Catracho, and no land should be rented. In the second season, the area planted to maize should also be reduced by more than 90% on average, no beans should be produced, and significant acreage (1.48 ha) should be allocated to Catracho (Table 1). Land rental should increase to the maximum available, 1 ha.

As the level of risk aversion increases with this model, the first season crop plan should shift more heavily to Catracho, with about equal area in maize/maicillo and Catracho. Essentially no land should be rented. In the second season, the allocation should again comprise a minor amount of maize. The remaining plantings should be diversified between Sureño and Catracho, and average land rental should be decreased only slightly from the maximum allowable, 1 ha. It is noteworthy that the results for the EIUM with the higher level of risk aversion are quite similar to the results for the EDUM with the lower level of risk aversion. This is consistent with the theoretical result that there is some risk aversion in our formulation of EDUM even when the parameter ρ is set to zero.

Several results are common to the two models with the lower level of risk aversion. First, the total crop area is almost the same in both models in both seasons. Total crop area is mainly determined by the cash available at planting time, the marginal utility of that cash for consumption versus investment opportunities, and the availability of labor and opportunity cost of labor for off-farm employment. In both models, the farmer begins with the same inventory. Therefore, both models reflect similar crop area in the first season. Second, the cropping plan in the first season is dominated by the traditional maize/maicillo intercrop and Catracho in both models. The intercrop activity helps relax the harvest time labor constraint in the first season, since local sorghum will not be harvested until the second season. Although, Catracho is more labor and capital intensive, its yield is sufficiently high to be attractive. Third, the adoption of the new technology permits more intensive land use. The farmer is relatively less dependent on rented land in both seasons. This is achieved by reducing the area in the intercrop, thereby allowing the farmer to plant more area in the second season, as compared to the base scenario.

Despite these similarities, the results of the EDUM model are more sensitive to risk aversion. Moreover, the crop plan with the EDUM is more diversified than with the EIUM, especially with higher risk aversion. This is because the direct utility maximizer is concerned with having a diverse diet beyond the subsistence levels, while the indirect utility maximizer is concerned only with the income obtained from production (net of fixed subsistence requirements).

The effect of introducing new technology on expected consumption expenses is smaller for EDUM (23 and 16% at the lower and higher risk aversion levels, respectively), than for EIUM (30 and 29% at the lower and higher risk aversion levels, respectively) (see Table 1). This is to be expected because the level of adoption of the new varieties is lower with the EDUM model. Risk aversion has little effect on expected consumption expenses for the EIUM model but a significant effect on expenses for the EDUM model. The variance and skewness of the distribution of expected consumption expenses for the EDUM model is lower than for the EIUM model (Table 1).

The introduction of the new technologies on these small hillside farms of southern Honduras is predicted by both models to change the farming practices in terms of cropping activities, total crop land (hence, land rented) and cropping intensity. These changes result in substantial changes in farm income, consumption behavior, and marketed surplus. However, the two models differ with respect to which variety will be adopted and with respect to the amount of land planted to the new technologies. The EIUM tends to overestimate the extent of adoption, especially with risk aversion. This is because the direct utility model recognizes the tradeoffs between consumption and investment in the new technology in the first stage when the marginal value of cash is high. The overestimation of adoption by EIUM is also related to household's desire to satisfy higher levels of nutrition with a diverse consumption bundle rather than merely the subsistence levels. To the extent that subsistence farmers vary their consumption in response to production and market outcomes, the EDUM approach should provide more realistic predictions of technology adoption.

5.3. Nutrition impacts of new technology

Much technology design and assessment work in developing countries has focused on the food supply dimension of new cereal technologies. Nonetheless, the modern theory of agricultural development emphasizes that there should be significant impacts of a new technology on household food consumption and nutrition. The analysis of the demand aspects of technology adoption under uncertainty is a major emphasis of the EDUM model. Even the household models literature for the most part treats this subject only under certainty (for example, see De Janvry et al., 1992 for a dual approach, or Omamo, 1998 for a primal approach to the household model). Because the EDUM model predicts optimal consumption levels under risk aversion, this model can be useful in predicting optimal marketed surplus of goods produced on the farm and the changes resulting from introduction of new technology. This type of analysis is ignored by the conventional EIUM model. Thus, only EDUM results are discussed here.

The results of the EDUM model indicate that adoption of the new technology would help the household to increase its consumption of nutrients (calories and protein), and nonfood. The results in Tables 2 and 3 illustrate the substantial extent to which the model predicts variation in the household consumption pattern in response to realized yields and prices.

With risk neutrality, total consumption of basic cereals (maize, sorghum, and rice) increases modestly by 11% in the first season, 12% in the second season, and 5.6% in third season. Overall, consumption of cereals increases by 10%. As a result, the total calories consumed by the household increases by 13.5% (Table 2).

On the other hand, consumption of beans, the major protein source, increases substantially with the introduction of new technology. The percentage increase in bean consumption is 43.2% in the first season, 45.2% in the second season, and 64.9% in the third season (Table 2). The consumption of beans in total increased by 50.8%. Meat consumed by the household comes mainly from chicken raised on the farm with the balance being purchased. Meat consumption shows no increase in the first season, but 43.5 and 64.3% in the second and third seasons, respectively. Because of the financial constraints in the first season, low initial capital, and the high rate of return for the new technology, meat consumption does not change with technology adoption during the first season. However, in the later seasons the farmer will have more cash available and more grain to feed the chickens. The increase in consumption of beans and meat increases average protein consumption of the household by 18.9%.

Consumption of other food and nonfood goods also increased significantly. This increase ranges from 10 to 48% with an average increase of 22%. Expenditures on this group of goods amount to 24% of total expenditures on average. This expenditure translates into increased demand for goods and services produced off-farm. This is important because it means an improvement in the standards of living of the farm population and increased income for employment outside the farm sector.

The relatively more risk-averse household depends more on goods produced on the farm. It purchases and consumes less meat and rice, substituting sorghum and beans (Table 3). Consumption of sorghum and beans is substantially higher as compared to the risk neutral case. Sorghum is considered an important substitute for maize, the main staple, as a human food in these rural areas as it helps eliminate rural malnutrition, especially in adverse rainfall years (Lopez-Pereira, 1990; p. 85). With the tendency toward lower meat consumption and higher cereal consumption, the risk averse farmer places more emphasis on increasing the intake of calories (by 30.7%) than protein consumption (9.1%). Nevertheless, the farmer would still increase expenditures on other foods and nonfood by 19.8%.

The significance of these results can be shown by analyzing the nutritional situation of farmers in rural Honduras. It has been reported that the average daily intake of calories of 1716 calories represents a deficit of 20% with respect to the accepted minimum standard of adequacy of 2138 (Garcia et al., 1987). Compared to the minimum accepted levels, the EDUM predicts that the optimum levels of the adult daily intake are 2304 calories and 59 g of protein, on average, prior to the introduction of the new technology. With the introduction of the new technology, the average daily intake of calories and protein increases to 2615 calories and 70 g of protein. Clearly, the introduction of these new technologies would help offset nutritional deficiencies even for the moderately risk averse farmer.

Table 2
Household consumption patterns under lower risk aversion

Commodity	Base technology			New technology			Percent change[a]
	Minimum	Mean	Maximum	Minimum	Mean	Maximum	
First season							
Maize (kg)		196.6			217.7		10.7
Sorghum (kg)		84.9			94.9		11.8
Rice (kg)		29.4			32.9		11.9
Beans (kg)		38.2			54.7		43.2
Meat (kg)		60.0			60.0		0.0
Nonfood ($)		63.9			70.3		10.0
Second season[b]							
Maize (kg)	284.0	335.1	384.4	227.0	381.3	658.4	13.8
Sorghum (kg)	114.6	151.7	204.6	85.6	164.7	338.1	8.6
Rice (kg)	29.3	48.2	65.2	32.7	54.4	84.1	12.9
Beans (kg)	52.4	71.5	93.9	53.4	103.8	284.1	45.2
Meat (kg)	33.5	45.7	61.9	43.1	65.6	65.1	43.5
Nonfood ($)	97.2	104.4	114.4	103.0	119.1	379.0	14.1
Third season[b]							
Maize (kg)	126.0	208.7	447.5	85.9	213.4	346.7	2.3
Sorghum (kg)	51.1	88.6	206.4	34.1	95.0	410.9	7.2
Rice (kg)	9.3	28.2	45.0	12.1	35.2	56.2	24.8
Beans (kg)	8.8	49.9	118.1	2.1	82.3	165.5	64.9
Meat (kg)	13.8	31.4	68.9	3.4	51.6	100.2	64.3
Nonfood ($)	45.6	60.9	83.6	42.5	90.6	637.4	48.8
Total consumption							
Maize (kg)	606.6	740.4	1004.3	530.6	812.5	1155.1	9.7
Sorghum (kg)	250.5	325.2	495.1	214.6	354.6	829.9	9.0
Rice (kg)	71.2	105.8	138.5	77.8	122.6	165.4	15.9
Beans (kg)	100.9	159.6	233.2	130.4	240.7	502.3	50.8
Meat (kg)	107.3	137.1	190.8	108.9	177.2	324.3	29.2
Nonfood ($)	208.0	229.4	261.9	217.9	279.9	1086.7	22.0
Nutrients							
Energy (Kcal)	3938	4793	5593	4352	5442	6422	13.5
Protein (kg)	100	122	142	102	145	198	18.9

[a] Evaluated at the mean consumption.
[b] Second and third stage decisions are conditional on the yield outcome in stage one. Hence, these decisions have distribution, and the means, minimum and maximum are reported in this table.

5.4. New technology and marketed surplus

Consumption behavior of the household has significant implications for the effect of new technology on marketed surplus. The expected direct utility maximization model allows the estimation of these effects in situations where product prices vary by state of nature. With base technology, the risk neutral household is a net seller of both maize and sorghum and a net buyer of beans on average (Table 4). At higher levels of risk aversion, the household is a net seller of all crops (Table 4). The introduction of the new technology results in substantial increases in marketed surplus, due to the changes in output and consumption patterns. By increasing the profitability of sorghum relative to beans and maize (particularly at low levels of risk aversion), the farmer is able to produce substantial amounts of sorghum at the expense of his output of beans and maize. Hence, he becomes a net buyer of both. However, he is able to market substantially more sorghum.

Due to risk aversion, the farmer diversifies across crops in order to ensure a more diverse consumption

Table 3
Household consumption patterns under higher risk aversion

Commodity	Base technology			New technology			Percent change[a]
	Minimum	Expected	Maximum	Minimum	Expected	Maximum	
First season							
Maize (kg)		175.2			200.0		14.2
Sorghum (kg)		76.0			79.4		4.4
Rice (kg)		26.1			27.4		5.0
Beans (kg)		22.7			35.0		54.2
Meat (kg)		60.0			60.0		0.0
Nonfood ($)		57.7			62.5		8.3
Second season[b]							
Maize (kg)	242.8	298.2	349.9	102.1	418.4	790.5	40.3
Sorghum (kg)	88.5	109.8	131.5	86.0	247.9	547.6	125.8
Rice (kg)	31.6	49.7	68.6	10.8	44.2	341.5	−11.1
Beans (kg)	31.5	47.2	73.7	27.0	77.7	103.0	64.6
Meat (kg)	89.2	128.7	168.3	17.8	29.3	72.6	−77.2
Nonfood ($)	89.4	94.6	100.2	87.1	106.4	113.2	12.4
Third season[b]							
Maize (kg)	103.0	136.2	296.6	63.0	194.0	511.5	42.4
Sorghum (kg)	17.9	56.6	114.7	1.1	113.6	455.3	100.7
Rice (kg)	10.8	37.6	65.8	1.7	41.1	172.4	9.3
Beans (kg)	6.2	29.2	94.6	0.9	52.1	133.0	78.4
Meat (kg)	3.0	28.0	117.8	2.0	51.6	308.5	84.3
Nonfood ($)	44.4	52.5	85.6	44.2	76.7	338.8	46.1
Total consumption							
Maize (kg)	534.8	609.5	813.1	365.1	812.5	1502.0	33.3
Sorghum (kg)	202.7	242.5	313.0	215.4	441.0	1001.4	81.9
Rice (kg)	68.9	113.5	156.0	40.0	112.7	403.7	−0.7
Beans (kg)	63.5	99.1	158.4	62.9	164.9	224.2	66.4
Meat (kg)	157.5	216.8	316.3	86.8	140.9	386.3	−35.0
Nonfood ($)	192.7	204.9	243.1	194.2	245.6	508.1	19.8
Nutrients							
Energy (kcal)	3752	4201	4780	3838	5491	6985	30.7
Protein (kg)	100	121	149	93	132	172	9.1

[a] Evaluated at the mean consumption. Consumption of goods other than nonfood is in kilograms per family and nonfood is in US dollars.

[b] Second and third stage decisions are conditional on the yield outcome in stage one. Hence, these decisions have distribution, and the means, minimum and maximum are reported in this table.

bundle on average. In this case, although less is marketed in comparison to the risk neutral farmer, some of each crop is sold, even with traditional technology. When new technology is introduced, the farmer substitutes the increase in beans and sorghum surpluses for a decreased surplus of maize (Table 4).

The implication of this is quite important for trade policy. The challenge for the policymaker is to create excess demand for sorghum and excess supply for maize and beans in either the domestic or the world market. The main expansion area for demand growth for sorghum will be the increasing feed demand as qualitative shifts in the diets accelerate towards greater meat consumption with income growth. Sorghum is an important feed. Over the period 1976–1989, feed use of sorghum was 83% of total utilization of grains (Lopez-Pereira et al., 1994).

The above results are consistent with development literature in that higher income, generated from adoption of new technology, allows increased access to a larger and more varied diet as well as improved nutrition. In addition, the higher income has translated

Table 4
Average quantities of grains marketed with low and high risk aversion

	Base technology			New technology		
	Maize	Sorghum	Beans	Maize	Sorghum	Beans
Low risk aversion						
Purchases						
First season	0.0	0.0	3.2	125.7	0.0	19.7
Second season	0.0	331.0	71.5	6.0	0.0	103.8
Third season	32.2	0.0	75.6	314.2	1.7	117.4
Total	32.2	331.0	150.3	445.9	1.7	240.8
Sales[a]						
First season	3.4	11.2	0.0	0.0	155.1	0.0
Second season	559.1	0.0	0.0	0.0	741.9	0.0
Third season	248.4	454.4	12.0	82.6	1754.0	0.0
Total	810.9	465.6	12.0	82.6	2551.0	0.0
Net surplus	778.7	134.6	−138.3	−394.1	2549.3	−240.0
High risk aversion						
Purchases						
First season	0.0	0.0	0.0	0.0	0.0	0.0
Second season	0.0	110.3	132.7	1.2	4.1	0.0
Third season	2.3	0.8	0.0	0.7	8.2	0.5
Total	2.3	111.1	132.7	1.9	12.3	0.5
Sales[a]						
First season	24.8	47.5	12.3	0.0	170.6	0.0
Second season	737.9	14.3	0.0	207.1	163.5	2.2
Third season	3.0	113.3	131.8	37.1	328.6	28.2
Total	765.7	175.1	144.1	244.2	662.7	30.4
Net surplus	763.4	64.0	11.5	242.3	650.4	29.9

[a] Sales are net of feed consumption of chicken equivalents of meat purchases expressed in kilograms.

into increased demand for other goods and services produced in other parts of the economy stimulating economic growth and employment. The results also indicate that the amount of marketed surplus and timing of sale of the crop will change due to changes in output and consumption behavior.

6. Conclusions

This study develops and demonstrates procedures for modeling agricultural technology adoption decisions in a subsistence-farming context. The method is based on expected direct utility maximization (EDUM) using a nested Stone–Geary utility formulation that incorporates subsistence quantities for broad aggregates of protein, calories, and other consumption goods. While the approach requires somewhat more computation than traditional expected indirect utility maximization (EIUM), it was quite practical for this problem, requiring about twice the computation time.

The proposed framework avoids decoupling production and consumption decisions to obtain more credible estimates of consequences of new technologies for production, household nutrition, and marketed surplus. Substantial price variability and correlation between prices and local yields is often a characteristic of developing country situations. EDUM avoids overstating the effect of technology adoption on marketed surplus by reflecting increased on-farm consumption and shifts in the consumption bundle. EDUM also avoids understating the effect of technology adoption on improving nutrition. This work extends the household modeling approach to problems with risk, and thus complements prior work in both the integrated analysis of production/consumption decisions and stochastic decision analysis.

Appendix A. Cereal consumption lower bounds derivation

In the presence of nonlinear constraints, nonlinear programming systems typically will evaluate the objective function and constraint functions at points that are infeasible during the solution process (Gill et al., 1981). If the objective and constraint functions are globally defined (i.e. without regard to feasibility), then this does not present a problem. However, in the case at hand where the objective is comprised of Cobb–Douglas aggregations nested under a Stone–Geary function, the values of the individual Cobb–Douglas aggregations must always exceed the subsistence levels for the aggregations. Hence, even if nonlinear constraints are imposed that require that the aggregations exceed the subsistence levels, these constraints may be violated during the solution process, leading to breakdown of the solution procedure.

On the other hand, if all constraints are linear, then nonlinear programming systems (e.g. GAMS/MINOS) are often designed to restrict evaluations of the (potentially nonlinear) objective functions to points that are feasible. Hence, it is desirable in the present case to design linear constraints that will result in values for the aggregations that always exceed subsistence levels. One approach to achieve this goal is to develop piecewise linear approximations to the nonlinear constraints. The alternative chosen here is to develop simple bound constraints on the individual-commodity consumption variables that will automatically satisfy the nonlinear constraints.

To develop the bound constraints, it is sufficient to focus on a single aggregation and a single state of nature (The procedure is applied separately to each aggregation with positive subsistence level, and each state of nature). Given the state of nature, the prices are fixed. For notational simplicity, the indices for the state of nature and aggregate will be suppressed. Hence, the subscripts refer to the indices of goods within the aggregate. The requirement is that the Cobb–Douglas aggregate exceeds the subsistence level, or

$$A\prod_i C_i^{\alpha_i} > \gamma$$

where A denotes the scaling constant for the aggregate, C_i the consumption of the ith good in the given aggregate and state of nature, α_i the value share of the good within the nest and state of nature, and γ the subsistence level for the aggregate.

The optimality conditions with respect to these variables is such that the optimal consumption levels will be proportional to the ratio α_i/P_i where P_i is the price of the ith good in the given state of nature. This means that the left-hand side of the above inequality can be written as:

$$A\prod_i \left(\frac{\alpha_i}{P_i}K\right)^{\alpha_i}$$

Now, K can be chosen so that this quantity exceeds γ by a small amount, say δ, and then lower bounds can be set as $C_i \geq K\alpha_i/P_i$. This choice results in a set of linear constraints such that the Cobb–Douglas aggregations will always exceed their subsistence levels, and the objective will be defined at every feasible point. The only difficulty is that upon solving the problem, it may be the case that the lower bound on C_i may be active in the solution. If this is the case, then for the state of nature and aggregate, the value of δ is reduced by half, new bounds are computed and the problem is solved again. It is known that this procedure will eventually produce a solution in which none of the lower bounds is active because the marginal utility of each good in the aggregate approaches infinity as the value of the aggregate approaches γ.

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