Appendix 2—Incorporating Technology Adoption in the Farm Household Model

The Theoretical Framework

This model combines in a single framework the technology adoption and off-farm work decisions by the operator and spouse and follows the analysis developed by Fernandez-Cornejo et al. (2005). The model expands the farm household model offered by Huffman (1991) with several additions to allow for technology adoption. According to the agricultural household model, farm households maximize utility U subject to income, production technology, and time constraints. Household members receive utility from goods purchased for consumption G, leisure (including home time) $L = (L_o, L_s)$ for the operator and the spouse, and from factors exogenous to current household decisions, such as human capital $H = (H_o, H_s)$, and other factors Ψ (including household characteristics and weather). Thus:

(1) $\quad Max\ U = U(G, \mathbf{L}, \mathbf{H}, \Psi)$

Subject to the constraints:

(2) $\quad P_g G = P_q Q - \mathbf{W}_x \mathbf{X}' + \mathbf{W}\mathbf{M}' + A$ (income constraint)

(3) $\quad Q = Q[X(\Gamma), \mathbf{F}(\Gamma), \mathbf{H}, \Gamma, \mathbf{R}], \quad \Gamma \geq 0$ (technology constraint)

(4) $\quad \mathbf{T} = \mathbf{F}(\Gamma) + \mathbf{M} + \mathbf{L}, \mathbf{M} \geq 0$ (time constraint)

where P_g and G denote the price and quantity of goods purchased for consumption; P_q and Q represent the price and quantity of farm output; $\mathbf{W}_x$ and $\mathbf{X}$ are the price and quantity (row) vectors of farm inputs; $\mathbf{W} = (W_o, W_s)$ represents off-farm wages paid to the operator and spouse; $\mathbf{M} = (M_o, M_s)$ is the amount of time working off-farm by the operator and spouse; $\mathbf{F} = (F_o, F_s)$ is the amount of time working on the farm by the operator and spouse; A is other income, including income (from interest, dividends, annuities, private pensions, and rents) and government transfers (such as Social Security, retirement, disability, and unemployment); $\mathbf{R}$ is a vector of exogenous factors that shift the production function, and $\mathbf{T} = (T_o, T_s)$ denotes the (annual) time endowments for the operator and spouse. The production function is concave and has the usual regularity characteristics. Some technologies offer simplicity and flexibility that translate into reduced management time, freeing time for other uses. In these cases, the amount of time working on the farm by the operator and the spouse $\mathbf{F}$ (and possibly the use of other farm inputs $\mathbf{X}$) is a function of Γ, the adoption intensity (extent of adoption) of the technology. A technology-constrained measure of (cash) household income is obtained by substituting (3) into (2) (Huffman, 1991):

(5) $\quad P_g G = P_q Q[X(\Gamma), \mathbf{F}(\Gamma), \mathbf{H}, \Gamma, \mathbf{R}] - \mathbf{W}_x \mathbf{X}(\Gamma)' + \mathbf{W}\mathbf{M}' + A$

The first order conditions for optimality (Kuhn-Tucker conditions) are obtained by maximizing the Lagrangian expression $\mathscr{L}$ over $(G, \mathbf{L})$ and minimizing it over the Lagrange multipliers (λ, μ), where $\mu = (\mu_0, \mu_s)$:

(6) $\mathscr{L} = U(G, \boldsymbol{L}, \boldsymbol{H}, \Psi) + \lambda \{ P_q Q[\boldsymbol{X}(\Gamma), \boldsymbol{F}(\Gamma), \boldsymbol{H}, \Gamma, \boldsymbol{R}] - \boldsymbol{W}x\, \boldsymbol{X}(\Gamma)' + \boldsymbol{W}\, \boldsymbol{M}' + A - P_g G \} + \boldsymbol{\mu}\ [\boldsymbol{T} - \boldsymbol{F}(\Gamma) - \boldsymbol{M} - \boldsymbol{L}]$

The off-farm participation and adoption decisions may be obtained from the following Kuhn-Tucker conditions:

(7) $\partial\mathscr{L}/\partial\boldsymbol{X} = \lambda\, (P_q\, \partial Q/\partial\boldsymbol{X} - \boldsymbol{W}_x) = \boldsymbol{0}$

(8) $\partial\mathscr{L}/\partial F = \lambda\, Pq\, \partial Q/\partial F - \boldsymbol{\mu} = \boldsymbol{0}$

(9) $\partial\mathscr{L}/\partial\Gamma = \lambda\{P_q[(\partial Q/\partial X)(d\boldsymbol{X}/d\Gamma)' + (\partial Q/\partial\boldsymbol{F})(d\boldsymbol{F}/d\Gamma)' + \partial Q/d\Gamma] - \boldsymbol{W}_x (d\boldsymbol{X}/d\Gamma)'\} - \boldsymbol{\mu}\, (d\boldsymbol{F}/d\Gamma)' \leq 0,$

$$\Gamma \geq 0,\ \ \Gamma \cong \partial\mathscr{L}/\partial\Gamma = 0$$

(10) $\partial\mathscr{L}/\partial\boldsymbol{M} = \lambda\, \boldsymbol{W} - \boldsymbol{\mu} \leq 0,\ \ \boldsymbol{M} \geq 0,\ \ \boldsymbol{M}(\lambda\, \boldsymbol{W} - \boldsymbol{\mu}) = 0$

(11a, b) $\partial\mathscr{L}/\partial G = U_G - P_g\, \lambda = 0,\ \partial\mathscr{L}/\partial\boldsymbol{L} = \boldsymbol{U}_L - \boldsymbol{\mu} = \boldsymbol{0}$

(12) $P_q\, Q[\, \boldsymbol{X}(\Gamma), \boldsymbol{F}(\Gamma), \boldsymbol{H}, \Gamma, R] - \boldsymbol{W}_x\, \boldsymbol{X}(\Gamma)' + \boldsymbol{WM}' + A - P_g\, G = 0$

(13) $\boldsymbol{T} - \boldsymbol{F}(\Gamma) - \boldsymbol{M} - \boldsymbol{L} = \boldsymbol{0}$

where U_L, U_G are the partial derivatives of the function U. Without loss of generality, both the operator and spouse are assumed to have positive optimal hours of leisure and farm work, i.e., equation (8) and (11b) are equalities.

The off-farm participation decision conditions for the operator and the spouse may be obtained from the optimality conditions for off-farm work, equation (10), together with equations (8) and (11b):

(14) $\mathrm{W} \leq \boldsymbol{\mu}/\lambda = \mathrm{P_q}\ \partial Q/\partial F$

where $\boldsymbol{\mu}/\lambda$ is equal to the marginal rate of substitution between leisure and consumption goods (from equations 11a and 11b) and $P_q\ \ \partial Q/\partial F$ represents the value of the marginal product of farm labor for the operator and the spouse. Examining the components of (14), $W_i < \boldsymbol{\mu}_{\mathrm{i}}\, /\lambda$ (strict inequality) indicates that the total time endowment for the operator ($i = o$) or spouse ($i = s$) is allocated between farm work and leisure; optimal hours of off-farm work are zero (corner solution), i.e., $M_i{}^* = 0$. On the other hand, if $W_i = \boldsymbol{\mu}_{\mathrm{i}}\, /\lambda$, optimal hours of off-farm work may be positive ($M_i{}^* > 0$) and $W_i = \boldsymbol{\mu}_{\mathrm{i}}\, /\lambda = P_q\ \ \partial Q/\partial F_i$ (interior solution) (Lass et al., 1989; Huffman, 1991; Kimhi, 1994; Huffman and El-Osta, 1997). In this case, the value of the marginal product of farm labor is equal to the off-farm wage rate.[27]

When an interior solution for $\boldsymbol{M}$ occurs, equations (7) and (8) can be solved together, independently of the rest of the Kuhn-Tucker conditions, to obtain the demand functions for onfarm labor, i.e., the optimal production and consumption decisions can be separated since the off-farm wage determines the value of the operator's and spouse's time ($\mathrm{W} = \boldsymbol{\mu}/\lambda$) (Huffman and Lange, 1989; Huffman, 1991).[28]

[27]The marginal value of time of the farm operator (or spouse) when all his/her time is allocated to farm work and leisure and none is allocated to off-farm work ($P_q\ \ \partial Q/\partial F_i\ |_{Mi\,=\,0}$) represents the shadow value of farm labor and is called the reservation wage for off-farm work for the operator (i = o) or spouse (i = s). In this context, the operator (or spouse) will work off-farm when his/her reservation wage is less than the anticipated off-farm wage rate and will not work off-farm otherwise. Assuming that both the operator and spouse face wages that are dependent on their marketable human capital characteristics ξi , local labor market conditions, and job characteristics Ω, but not on the amount of off-farm work (Huffman and Lange, 1989; Huffman, 1991; Tokle and Huffman, 1991), the off-farm market labor demand functions are $W_i = W_i\ (\xi i,\ \Omega\ ), (i = o, s).$

[28]Moreover, when an interior solution occurs, from (10), (11a), and (11b) we obtain $\boldsymbol{U}_L/U_G = \boldsymbol{W}/P_{\mathrm{g}}$; that is, the marginal rate of substitution between consumption goods and leisure is equal to the ratio of the wage rate and the price of consumption goods.

The demand function for onfarm labor is then $\boldsymbol{F^*} = F(\boldsymbol{W}, \boldsymbol{W}_x, P_q, \boldsymbol{H}, \Gamma, R)$ and the demand for purchased farm inputs $\boldsymbol{X^*} = X(\boldsymbol{W}, \boldsymbol{W}_x, P_q, \boldsymbol{H}, \Gamma, \boldsymbol{R})$. These optimal input demand functions are substituted in the production function to obtain the supply of farm output $Q^* = S(\boldsymbol{W}, \boldsymbol{W}_x, P_q, \boldsymbol{H}, \Gamma, \boldsymbol{R})$ and the maximum net household income may be expressed as:

$$(15) \qquad NI^* = P_q\, S(\boldsymbol{W}, \boldsymbol{W}_x, P_q, \boldsymbol{H}, \Gamma, \boldsymbol{R}) - W_x\, \boldsymbol{X^*}' + \boldsymbol{W}\boldsymbol{M}' + A$$

Solving jointly equations (10), (11), and (15) we obtain the demand for leisure $\boldsymbol{L^*} = L(\boldsymbol{W}, P_g, NI^*, \boldsymbol{H}, \Psi, \boldsymbol{T})$ and for consumption goods $G = G(\boldsymbol{W}, P_g, NI^*, \boldsymbol{H}, \Psi, \Gamma, \boldsymbol{T})$. The supply function for off-farm time is obtained by substitution of the optimal levels of leisure hours and farm work hours (Huffman, 1991):

$$(16) \qquad \boldsymbol{M^*} = \boldsymbol{T} - \boldsymbol{F^*} - \boldsymbol{L^*} = M(\boldsymbol{W}, \boldsymbol{W}_x, P_q, Pg, NI^*, \boldsymbol{H}, \Psi, \Gamma, \xi i, \Omega, \boldsymbol{R}, \boldsymbol{T})$$

Finally, a reduced-form expression of total household income is obtained by:

$$(17) \qquad NI^* = NI(\boldsymbol{W}_x, P_q, P_g, A, \boldsymbol{H}, \Psi, \Gamma, \boldsymbol{R}, \boldsymbol{T})$$

As Huffman (1991) notes, when optimal hours of off-farm work hours for the operator or the spouse are zero, the decision process is not recursive and production and consumption decisions must be made jointly. In this case, the arguments for the reduced-form expression of household income are the same as those in (17) but exclude the exogenous variables related to the job characteristics and labor marketability.

The technology adoption decision condition is obtained from the optimality conditions, equation (9) and equations (8) and (11b), noting that the expression in brackets in (9) is the total derivative $dQ/d\Gamma$. Thus, we obtain:

$$(18) \qquad Pq\, dQ/d\Gamma - \boldsymbol{W}_x\, (d\boldsymbol{X}/d\Gamma)' - (\boldsymbol{\mu}/\lambda)(d\boldsymbol{F}/d\Gamma)' \le 0$$

But from (11a) and (11b) $\boldsymbol{\mu}/\lambda = P_g\, (U_L/U_G)$; then:

$$(19) \qquad P_q\, dQ/\Gamma - \boldsymbol{W}_x\, (d\boldsymbol{X}/d\Gamma)' - P_g\, (U_L/U_G)(d\boldsymbol{F}/d\Gamma)' \le 0$$

The left-hand-side of this expression may be interpreted as the marginal benefit of adoption $P_q\, dQ/d\Gamma$ minus the marginal cost of adoption, which includes the marginal cost of the production inputs $\boldsymbol{W}_x\, (d\boldsymbol{X}/d\Gamma)'$ and the marginal cost of the farm work $P_g\, (\boldsymbol{U}_L/\boldsymbol{U}_G)(d\boldsymbol{F}/d\Gamma)'$ (of the operator and the spouse) brought about by adoption (could be negative if adoption saves managerial time), valued at the marginal rate of substitution between leisure and consumption goods (which, when off-farm work hours are positive, equals the off-farm wage rate). It will not be optimal to adopt if the inequality is strict (corner solution), wherein the marginal benefit of adoption falls short of the marginal cost of adoption. An interior solution for the optimal extent of adoption will occur when the equality is strict or when the value of the marginal benefit of adoption is equal to the marginal cost of adoption.

Given the cross-sectional nature of the data, one can use the implicit function theorem to derive expressions for off-farm labor supply for farm operator and spouse and technology adoption (which affects off-farm labor supply of farm operators and spouses) that are functions of wages, prices, human capital, nonlabor income, and other exogenous factors. These factors are replaced in reduced-form representations of labor supply and adoption by observable farm, operator, and household characteristics, including human capital. The "ambient variables" (family size, access to urban areas), which might affect the productive capacity of the farm operator and the spouse, are also included. The following section outlines the empirical model and estimation method used to conduct the analysis.

Empirical Model

A two-stage econometric model is specified. The first stage, the decision model, examines the off-farm work participation and the technology adoption decisions. The second stage is used to estimate the impact of adoption on household income.

A simplified "reduced form" approach is followed (Goodwin and Holt, 2002; Goodwin and Mishra, 2004) to specify the empirical model, rather than explicitly estimating a structural model of labor supply. In this approach, the reduced form of the decision model is obtained by specifying the endogenous variables ($\boldsymbol{M}$, $\boldsymbol{F}$, Q_g, $\boldsymbol{X}$) in terms of the exogenous variables, including $\boldsymbol{W}_x$, P_q, P_g, $\boldsymbol{H}$, Ψ, ξ_i, Ω, $\boldsymbol{R}$, $\boldsymbol{T}$. Equation (14), implied by the Kuhn-Tucker conditions, is central to the off-farm work decision of the operator and the spouse and equation (19) is central to the adoption decision. Thus, considering a first-order approximation (linear terms) and adding the stochastic terms, the empirical representation of the decision model, which includes the off-farm participation of the operator (20a) and spouse (20b), and the technology adoption decision (20c), is:

(20a) $$\boldsymbol{\beta_o} \boldsymbol{Z_o}' + \varepsilon_o \leq 0$$

(20b) $$\boldsymbol{\beta_s} \boldsymbol{Z_s}' + \varepsilon_s \leq 0$$

(20c) $$\boldsymbol{\beta_a} \boldsymbol{Z_a}' + \varepsilon_a \leq 0$$

where the (row) vectors Z_o, $\boldsymbol{Z_s}$, and $\boldsymbol{Z_a}$ include all the factors or attributes influencing linearly the off-farm participation (operator and spouse) and adoption decisions, and $\boldsymbol{\beta_o}$, $\boldsymbol{\beta_s}$, and $\boldsymbol{\beta_a}$ are vectors of parameters. Assuming that the stochastic disturbances are normally distributed, each of these equations may be estimated by probit. However, because the disturbances (ε_o , ε_s, ε_a) are likely to be correlated, univariate probit equations are not appropriate. Bivariate probit models have been used to model the off-farm employment decisions by the operator and spouse (Huffman and Lange, 1989; Lass et al., 1989; Tokle and Huffman, 1991). Since the decisions to work off farm and the technology adoption decision may be related, all three decisions are modeled together in a multivariate probit model (Greene, 1997). Formally, [ε_o , ε_s, ε_a] ~ trivariate normal (TVN) [$0,0,0;1,1,1;\rho_{12},\rho_{13},\rho_{23}$], with variances ρ_{ij} ($i = j$) equal to 1 and correlations ρ_{ij} ($i \neq j$) where $i, j = 1,2,3$.

The joint estimation of three or more probit equations was computationally unfeasible until recently because of the difficulty in evaluating high-order multivariate normal integrals. Over the past decade, however, the estimation has been made possible with Monte Carlo simulation techniques (Geweke et al., 1994; Greene, 1997).

The vector $\boldsymbol{Z}_i$ includes (i) farm factors, such as farm size and complexity of the operations; (ii) human capital (operator age/experience and education); (iii) household characteristics (such as the number of children); (iv) off-farm employment opportunities, which will depend on the farms' accessibility to urban areas and the change in the rate of unemployment in nearby urban areas; (v) farm typology; and (vi) government payments.[29] The factors or attributes influencing adoption, included in the vector $\boldsymbol{Z}_a$, are farm factors, human capital, farm typology, a proxy for risk (risk-averse farmers are less likely to adopt agricultural innovations), and crop/seed prices.

The second stage, the income impact model, provides estimates of the impact of adoption on household income after controlling for other factors. The empirical representation of this model—based on equation (17), the reduced-form expression of household income—is $NI^* = NI(\boldsymbol{W}_x, P_q, P_g, A, \boldsymbol{H}, \Psi, \Gamma, \boldsymbol{R}, \boldsymbol{T})$.

After linearizing this reduced form, separating out explicitly the adoption indicator variable, and appending a random disturbance å, assumed to be normally distributed, we have:

$$NI^* = \boldsymbol{\theta V}' + \alpha I + \varepsilon \quad (21)$$

where NI^* represents household income; $\boldsymbol{V}$ is a (row) vector of observable explanatory variables that may influence household income (other than technology adoption) such as prices, human capital, and "ambient variables" (family size, access to urban areas) that may affect the productive capacity of the farm operator and the spouse; I is an indicator variable for adoption ($I=1$ if adoption takes place and $I=0$ otherwise); and $\boldsymbol{\theta}$ and α are appropriately dimensioned parameters. The impact of adoption on household income is measured by the estimate of the parameter α. However, as noted by Stefanides and Tauer (1999), if α is to measure the impact of adoption on income of a representative farm, farmers should be randomly assigned among adopter and nonadopter categories. This is not the case, since farmers make the adoption choices themselves. Therefore, adopters and nonadopters may be systematically different and these differences may manifest themselves in farm performance and could be confounded with differences due purely to adoption. This situation, called self-selection, may bias the statistical results unless corrected (Fernandez-Cornejo et al. 2002).

To correct for self-selection bias, we follow Maddala (1983) and Greene (1995) and obtain consistent estimates of the parameters $\boldsymbol{\theta}$ and α by regarding self-selection and simultaneity (discussed earlier) as sources of endogenity. Because the dummy variable I cannot be treated as exogenous, instrumental variable techniques are used to purge the dependence of I. The predicted probability of adoption, obtained from the decision model, is used as an instrument for I in equation (21).

Unlike the traditional selectivity model, in which the effects are calculated (separately) using the subsamples of adopters and nonadopters, the impact model uses all the observations and is known as a "treatment effects model,"

[29]Following Goodwin and Holt (2002), some prices are not included in our empirical models since prices are approximately constant across households when data consist of cross-sectional observations taken at a point in time. We did include some prices, like the price of soybeans, but its coefficient was statistically insignificant.

used by Barnow et al. (1981). The treatment effects model consists of the regression $Y = \boldsymbol{\theta V'} + \alpha I + \varepsilon$ where the observed indicator variable I $(I = 1$ if $I^* > 0$ and $I = 0$ if $I^* \leq 0)$, indicates the presence or absence of some treatment (adoption of herbicide-tolerant crops in this case) and the unobserved or latent variable I^* is given by $I^* = \boldsymbol{\delta} Z_a' + \nu$(Greene, 1995).

Total household income (*NI**), as represented in (17), has two components: household income from farming (*FARMHHI*) and off-farm household income (*TOTOFI*). Household income from farming includes farm business household income, operator's paid farm income, household members' paid farm income, etc. (see detailed definitions in appendix table 1). Off-farm household income includes off-farm business income, income from operating other farm businesses, off-farm wages and salaries, etc.

The components of vector ***V*** include farm location and typology, operator age, education and experience, number of children, price of soybeans, a measure of specialization on soybean production, a measure of the extent of livestock operations, farm size, and proxies for local labor market conditions.

The data are obtained from the nationwide Agricultural Resource Management Survey (ARMS) developed by USDA (USDA, ERS, 2003). The ARMS survey is designed to link data on the resources used in agricultural production to data on use of technologies, other management techniques, chemical use, yields, and farm financial/economic conditions for selected field crops. The ARMS is a multiframe, probability-based survey in which sample farms are randomly selected from groups of farms stratified by attributes such as economic size, type of production, and land use.

The 2000 data set (used for the HT soybean and Bt corn case study) includes 17 soybean (corn) producing States: Arkansas, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Mississippi, Michigan, Minnesota, Missouri, Nebraska, North Carolina, Ohio, South Dakota, Tennessee, and Wisconsin. After selecting those farms that planted soybeans (corn) in 2000 and eliminating those observations with missing data, there were 2,258 observations available for the soybean analysis and 2513 observations for corn.

The 2001 corn data set (used for the yield monitor and conservation tillage case studies) includes observations of 17 corn-producing States. After eliminating observations with missing data, there were 1,763 observations available for analysis.

Because of the complexity of the survey design, a weighted least-squares technique is used to estimate the parameters using full-sample weights developed by the USDA's National Agricultural Statistics Service. Standard errors are estimated using a delete-a-group jackknife method (Kott, 1998; Kott and Stukel, 1997) where a group of observations is deleted in each replication. The sample is partitioned into r groups of observations (r = 15) and resampled, thus forming 15 replicates and deleting one group of observations in each replicate.

Appendix table 2 shows the parameter estimates α (equation 21) along with standard errors. These parameters may be interpreted as the derivatives of household income with respect to the probability of adoption and are used to obtain the elasticities shown in table 7.

Appendix table 1

Household (HH) income variable definitions

1. **Household income from farming (FARMHHI)** = Farm Business Income HH Share
+ Operator Paid on Farm
+ Household Members Paid on Farm
+ Net Income from Rented Land

Where:

Farm Business Income HH Share = Net Cash Farm Business Income
- Depreciation
- Gross Income from Rented Land
- Operator Paid Onfarm
- Income Due to Other Households

Net Cash Farm Income = Gross Cash Farm Income - Cash Operating Expenses

Gross Cash Farm Income = Crop and livestock income including CC loans + Other farm income (includes government payments, income from custom work and machine hire, income from livestock grazing, other farm-related income, income from farm land rented to others, fee income from crops removed under production contract, fee income from livestock removed under production contract).

Total Cash Operating Expenses (hired labor, contract labor, seed, fertilizer, chemicals, fuel, supplies, tractor and other equipment leasing, repairs, custom work, general business, real estate and property taxes, insurance, interest, purchased feed, purchased livestock).

2. **Off-Farm Household Income (TOTOFI)** = Off-farm business income
+ Income from operating other farm businesses
+ Off-farm wages and salaries
+ Interest and dividend income
+ Other off-farm income
+ Rental income

3. **Total Household Income (TOTHHI)** = Household Income from Farming (FARMHHI)
+ Off-Farm Household Income (TOTOFI)

Appendix table 2

Parameter estimates of probability of adoption term of the household income equation for technologies of varying managerial intensity

	Yield monitors			Bt corn			Conservation tillage			Herbicide-tolerant soybean		
	Estimate	std. err.	t-value	Estimate	std. err.	t-value	Estimate	std. err.	t-value	Estimate	std. err.	t-value
Onfarm household annual income	25.1	63.8	(0.39)	-13.9	10.9	(-1.29)	6.4	49.5	(0.13)	-30.4	29.8	(-1.02)
Off-farm household annual income	-124.9	35.3	(-3.54)	-36.7	36.2	(-1.07)	87.3	30.3	(2.88)	133.4	67.0	(1.99)
Total household annual income	-100.8	68.7	(-1.47)	-50.6	36.5	(-1.39)	93.9	51.3	(1.83)	104.1	59.0	(1.76)

Note. Standard errors calculated using the delete-a-group jackknife method.