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The Effects of Uncertainty on Landowner Conversion Decisions

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Foreword

This paper was written by Todd Schatzki, the 1994-1995 winner of the Joseph Crump Fellowship. The Fellowship is awarded each year to a PhD student focusing his or her research on a topic in the field of natural resource or environmental policy.

The Felllowship is a memorial to Joseph Crump of Houston, Texas, a noted scholar in his own right and a long-time friend to Harvard University and the Kennedy School of Government.

Henry Lee
Director
Environment and Natural Resources Program

Executive Summary

Land use is at the nexus of a number of important environmental problems, including biodiversity loss, global warming, wetland loss, and soil erosion. Federal and state governments, however, have tended not to integrate these concerns into the agricultural and forest sector policies having the most significant effect on land use patterns. Farm subsidies are a prominent example, often necessitating large subsequent programs (such as the Conservation Reserve Program and "sodbuster" provisions) to undo the externalities caused by earlier policies.

Land owner decisions to convert between agriculture and forests has critical impacts upon the production of these environmental benefits. Until recently, however, these decisions have received relatively little attention, and the existing explanations are still inadequate to explain some observed behavior, particularly the slowness of landowners to respond to rises in the returns of alternative uses. This slowness to convert has been evidenced by the existence of a large number of unexploited, but profitable, conversion opportunities. Explanations such as non- financial ownership benefits, liquidity constraints, information and technology constraints, decision-making inertia, land market imperfections, spatial affects on land value, and uncertainty have been suggested to explain this behavior, but little formal analysis has been made to test these explanations.

When the costs of converting the land cannot be retrieved if the owners wants to later reconvert (i.e. the conversion costs are sunk), conversion can only be justified if future benefits in the new use are in excess of future benefits in the old use plus conversion costs. If future returns are uncertain, the "hurdle price" which justifies conversion may be affected. Two models are considered. The first is a model of a risk averse owner maximizing the expected return from land consisting of assets in agriculture

and forests. Just as an owner of any asset portfolio will diversify her holdings in the face of uncertainty, the share of land in forests and agriculture will be more diversified than under an assumption of certain future returns. This model, however, may not adequately describe landowners in the Southern United States, since many owners will be specialized to only one use for technical reasons (e.g. the forest industry), many owners will have very large portfolios that reduce the diversification of each individual asset, and uncertainty may be reduced through futures or options.

In the second model, the land owner may value the option to delay conversion if waiting provides more information on the expected value of future returns, and the costs of delay are not large. In this model, conversion in either direction must be justified by larger benefits than would be implied by a standard net present value calculation, and thus conversion occurs less often. Simulations of conditions facing growers of several crops in the Southern U.S. suggest that the option to delay creates a small increase in the hurdle price necessary to convert land from agriculture to forest, and a large increase in the hurdle price necessary to convert from forests to agriculture.

The analyses suggest that uncertainty may play a significant factor in the decisions of land owners to convert land, though further statistical analyses are clearly warranted to confirm the tentative conclusions of this study. The importance of such analyses, however, are significant, particularly as Congress reconsiders the level of subsidies and stabilization programs to the agricultural sector -- programs that have historically reduced the financial uncertainty for those in agricultural production. Changes in such policies may have unintended effects, particularly if landowners now facing greater uncertainty must change uses in the face of reductions in agricultural supports.

I. Introduction

Land owners facing uncertain future profits may produce different decisions about when to convert land to alternate uses than owners with perfect knowledge of future prices, yields and costs. The effects of uncertainty upon land conversion decisions, however, has received relatively little attention. A growing number of theoretical models and empirical studies have analyzed the question of land conversion under certainty (Ehui, Hertel and Preckel, 1990; Kramer and Shabman, 1993; Parks and Murray, 1994; Pfaff, 1994; Stavins, 1995; Stavins and Jaffe, 1990). This paper hopes to extend the understanding of land conversion by analyzing the decisions of land owners with uncertain knowledge of future economic and production conditions.

Attention to land conversion has recently grown due to the loss of wetlands, the potential of carbon sequestration in forests to reduce global warming, and the loss of biodiversity and other public goods from deforestation. Understanding the effects of models of uncertainty on land conversion decisions may provide important insights in the development of policy addressing these environmental problems, or hoping to maintain a stable supply of agricultural and forest products. The past efforts of agricultural policy to stabilize market prices and farmer incomes may have significantly reduced the uncertainty facing farmers. Many of these policies are currently under reconsideration by Congress, potentially subjecting farmers to higher levels of uncertainty over future economic variables. The effects of these changes upon land conversion decisions may have repercussions for agricultural and timber output and the provision of the environmental benefits of land.

Reactions to uncertainty may also explain some past owner conversion behavior and the outcomes of previous policy efforts to convert land. A number of economic studies contend that large amounts of land currently used for agriculture in the southern United States would be more profitable if converted to forests (Parks, 1995; Hardie, 1984; USDA, 1988). The lack of response to apparently profitable options has been long observed in the forestry sector, where stumpage elasticities are extremely low (Cubbage and Haynes, 1988). Explaining such behavior may provide insights that are important to

achieving agricultural and forest policy goals. In addition, some programs promoting land conversion have been less effective than planned. The Conservation Reserve Program (CRP), which provides incentives for conversion of agricultural land to grasslands or forests, has achieved less than 40% of its conversion goal for forests (United States Congress, 1995; Trexler, 1991). Behavior under uncertainty may provide an explanation for why such conversions are difficult to achieve.

This paper develops two models of uncertainty, evaluates their ability to explain past land owner behavior, and considers the implications of behavior under uncertainty for policy. The first model, previously developed by Parks (1995), considers risk averse land owners optimizing a land portfolio with uncertain future profits from forestry and agricultural uses. The second model assumes that average revenues are stochastic and the decision to convert can be delayed indefinitely. Since the conversion investment is sunk, the option to delay investment may be valuable. Development of this concept draws from the recent literature in irreversible[2] investment under uncertainty (see Dixit and Pindyck, 1994). From this perspective, conversion costs are an irreversible investment since they are (literally) sunk into the specific parcel and are not mobile. Land owners' ability to delay conversion decisions to observe whether profits of the converted use decline in the future creates an often significant value to the option to waiting. Consequently, traditional net present value calculations which do not consider such options may predict too much conversion. Such hesitation to make investments may seem natural when the costs of going back to the old use are high and result in loss of the initial investment. Further, the assumption of risk aversion is not required to observe this effect.

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[2] Two meanings of irreversibility are often used, creating some confusion. In the first, irreversible means that the decision, once made, cannot be reversed through any means, such as the extinction of a species or the installation of home energy conservation improvements (Hassett and Metcalf, 1992). In the second meaning, however, irreversible is used synonymously with sunk investments. That is, the sunk investment, once made, cannot be reversed with out further costs. The conversion investments considered here are irreversible only in the latter sense.

The paper focuses upon conditions in southern United States[3], the most productive forest region in the country and the subject of much analysis (Hardie, 1984; Kramer and Shabman, 1993; Parks, 1995; Stavins, 1995; Stavins and Jaffe, 1990). Section 2 provides a background history of changes in land use and land owner characteristics in the South. Section 3 briefly outlines the effects of agricultural and forest policy upon private conversion decisions. In Section 4, a model of land owner decision-making under certainty is developed. Section 5 develops the two models of conversion investment under uncertainty, and analyzes their ability to explain observed land owner behavior. Section 6 provides the results of simulations of the model of investment with sunk costs based on conditions facing land owners in the South. Section 7 considers the implications of the models of uncertainty for public policy, including programs directly promoting land conversions and the unintended impacts of changes in existing agricultural subsidies and supports. Section 8 concludes.

II. Background History

Though no statistically accurate records of forest cover are available previous to 1952, historical trends are relatively clear. While the South was originally almost completely forested, settlement from the 1700's on resulted in significant clearing of land for pasture, crop production, timber removal and urban uses, such as roads and cities (USDA, 1988; Williams, 1993). During the 1800's, harvesting of old-growth timber accelerated and much of the harvested land was permanently converted to agricultural production or pasture (USDA, 1988). While net deforestation continued until the 1920's, the percentage of land in forests remained above fifty percent throughout most regions of the south (Williams, 1993). In the 1920's, a combination of the harvesting of the last old-growth forests, the agricultural recession, and the boll weevil infestation led to a

[3] The South is defined throughout as including the states: Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia.

reversal of the deforestation trend (USDA, 1988). The depression period and 1950's saw additional abandonments of cropland as agricultural demand, particularly for cotton, slackened, african-american labor migrated to the urban regions, and agricultural production moved to coastal and irrigated western regions (Williams, 1993; USDA, 1988). Table 3 shows the decline of cropland during the 1095's and early 1960's, as the amount of active cropland declined.

Reforestation[4] continued until the 1960's when agricultural clearing, particularly for soybean production, and urban growth began to overtake abandonment. The total forest area recorded in 1962 of 193 million acres, or nearly three fifths of land in the South, is likely the largest amount of forest in the South since initial colonization (See Table 1) (USDA, 1988)[5]. Since this time forest land has declined about 9 million acres to 182 million acres in 1985. Regional variation in land use change has been significant throughout the South. Conversion to agriculture has been significant in coastal regions and bottomland hardwood along the Mississippi river due to, among other things, significant public investment in irrigation and flood control. Inland areas, traditionally planted for cotton, have seen a significant degree of abandonment. Urbanization has led to significant forest clearing in some regions such as Florida (USDA, 1988).

Landowner characteristics have also changed significantly over time. Private ownership of forest land has always been the predominant form of tenure throughout the south (USDA, 1988). Currently, the 18 million acres, or 10%, of forest land in public ownership is likely the highest level of public ownership in history. Private forests are held by a variety of owners including the forest industry, farmers, corporate owners, and other individuals. While the vast majority of owners are private individuals with small woodlots, the majority of acreage is currently held by the forest industry or individuals

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[4] Reforestation includes both deliberate replanting of trees and the natural succession of forests after abandonment of agricultural land.

[5] There is some discrepancy between data on land use and forest ownership from various USDA sources. For land use information, where there is some discrepancy in forest land between the USDA(1988) and USDA (1995), USDA (1988) is assumed to be more accurate due to the studies detailed scope.[55]

with large holdings[6]. About 40% of forest land is in holdings of 1,000 acres of more, though about 70% of the forest owners have less than 10 acres. Compared to other regions in the United States, however, small woodlot owners control a large amount of total acreage -- woodlot owners with less than 500 acres own about 50% of the total acreage.

Ownership characteristics, such as technical knowledge, other investment options, and non-financial benefits to ownership, may affect the decision to make conversion investments. Since different ownership types may systematically have different characteristics, understanding these characteristics may be important to analyzing the appropriateness of different models for describing the behavior of different types of owners. Below is a description of different types of land owners, including their motivations for ownership, ability to derive full economic value from the land, and trends in acreage owned in the South:

Farmers -- Farmers have traditionally owned some forest land as a part of the farm, often to provide off-season income, allow for future expansion, or provide a secure financial asset. While farmers technical knowledge is greatest in crop or livestock production, farmers may also have some knowledge of forest management and markets. Though in the past farmers often used woodlots as a means of utilizing their off-season labor, management and harvesting is typically now done by contract forest managers and timber harvesters. Farmer ownership of forests is declining, though the exact degree is difficult to determine from the figures in Table 1 since many farmers are simply recategorized as "other individuals" as their primary source of income shifts to off-farm sources. In addition, many farms have been sold to individuals whose primary income is from off-farm sources. Some decline in farm ownership of forests is expected, though the total area of agricultural cropland is expected to remain constant (USDA, 1988).

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[6] Ownership statistics are taken from two sources (USDA, ; USDA, 1988) that provide relatively consistent results, though there are some discrepancies which may be the result of different surveys of inconsistent categorizations.

Forest Industry -- The forest industry is defined as any corporation or individual that has timber processing facilities. The forest industry owns forests principally to insure adequate supplies of raw inputs to production, though there is some evidence that availability of large inventories allows the industry to force smaller buyers to sell during periods of low prices. The forest industry has significant expertise in forest management and typically employs their own labor and management on their forest lands. Management experience with farmland is minimal, and it is unlikely that the forest industry owns much agricultural land. One trend throughout the South is for the forest industry to lease land from private individuals on long or short-term leases. In 1985, about 4 million acres were leased by the forest industry for periods longer than one rotation. Forest industry acreage has increased steadily over the past 40 years, though acreage may level off as the industry relies more upon leases with other private owners, future investment shifts to more intensive management, and other investment opportunities in the companies portfolios are pursued (USDA, 1988).

Corporations -- Corporate owners include insurance companies, banks, and other institutional investors (without timber processing facilities) who own timberland as one asset in large financial portfolios. Corporate investors currently hold a relatively small amount of timber (less than 10% of forest acreage), though acreage is expected to increase.

Other individuals -- "Other individuals" is a catch-all category for all other individuals not fitting into the farmer, forest industry, and corporate categories. This includes a wide-range of owners, including large family ownerships, part-time farmers (principle income from off-farm sources) and small woodlots attached to homesteads. Large owners tend to manage forest lands similar to other assets, though the ownership objectives of small owners tend to include many non-financial interests such as firewood, amenity, and retirement security. Since small woodlots (less than 500 acres) account for about one-half of the forest land in the south, these additional objectives may have a significant effect on conversion decisions. Small owners may find it more feasible to obtain exercise

in forestry through professional forest managers than in agriculture, where leasing is usually the only means for a non-active landowner to employ the land. Many small, part-time farmers, however, may accept lower returns on their land in order to maintain a farming lifestyle (Robinson, 1989). As these two countervailing effects suggest, small land owner behavior may differ from standard economic assumptions in many respects, making assessment of the likelihood of small owners maintaining land in forests or agriculture difficult.

The model of land conversion developed assumes basic profit maximizing behavior by land owners. Such a model suggests that conversion will occur if the net present value of future benefits from the converted use is greater than the net present value of the present use plus the conversion costs. A number of observations about current management suggest that such a model is not a completely accurate representation of conversion decision-making. First, large numbers of potentially profitable conversions, based on NPV calculations, are not being undertaken by owners. One study (USDA, 1988) indicates that almost 19 million acres have "medium"[7] potential for conversion to agriculture, and almost 22 million acres of agricultural land (about 12% of the agricultural base) would receive higher rates of return in forest. Other studies have indicated the potential for higher profitability of forests on existing agricultural land (Hardie, 1984; USDA, 1992). Second, the elasticity of supply for forest stumpage has traditionally been very low, indicating a relatively slow response to price changes (Cubbage and Haynes, 1988). Adams and Haynes (1980), for example, report a region elasticity of .47 for the forest industry, and .345 for non-industrial owners in the South (cited in Cubbage and Haynes, 1988). Stumpage can be provided both through conversion of agricultural land or more intensive management on existing stands. It is likely that the conversion response is significantly less than the management response, since the option to delay is valuable for the conversion investment but not for the management investment, which must be timed to forest growth and hence cannot be

[7] "Medium" is not defined. Of these 19 million acres, 4.5 million acres have a "high" potential conversion to agriculture.

delayed. Both of these observations suggest that there are factors slowing the conversion of land that may not be fully represented by the simple profit maximizing model.

A number of factors (some already alluded to) might explain why ownership behavior may not follow a simple profit maximization model. Among these are:

- *Technical and market information constraints* -- Availability of technical and market information in agriculture is generally relatively good. While large forest land owners may have good knowledge about forest management options, expected returns and market conditions, small woodlot owners generally have inadequate management information. Many small owners must rely on timber managers and contractors, though with limited experience (exacerbated by the infrequency of harvesting on small woodlots) it is often difficult to obtain reliable and honest service.

- *Non-financial ownership benefits* -- As noted above, many owners holds forest land and farmlands for the non-financial benefits they provide, such as residential amenities.

- *Higher return requirements for delayed forest returns* -- A higher return may be required of forest land due to the long delay between rotations (Hardie, 1984).

- *Decision-making inertia and liquidity constraints* -- Land management decision-making may occur infrequently, may have significant management costs, particularly for small owners, and may be constrained by lack of capital to invest in conversion.

- *Land market imperfections* -- Significant imperfections may exist in rural markets with relatively few transactions. Significant speculation may occur as well during periods of economic upturn.

- *Spatial effects on land value* -- The value of land, because it is spatially immobile, depends upon the size of the ownership to which it is attached and the attributes of adjacent parcels. The owner's ability to make use of optimal scale economies in production in both agriculture and forestry is thus affected by the parcel's specific spatial attributes. Significant fragmentation may mean that significant transaction costs are required to aggregate into economically viable holdings. The ability to sell of small parcels may similarly be limited depending upon access and adjacent uses.

- *Uncertainty over future prices or yields* -- As more fully developed in Sections 5-6, conversion decision under uncertainty may not follow standard net present value calculations due to the desire to diversify the agriculture/forest portfolio and the value of the option to delaying the conversion decision.

The likelihood of these factors affecting ownership decision-making will vary across ownerships types, as will the ability of different ownership types to utilize land in its most productive manner. The expectation is that profit-maximizing behavior increases with owner size as the effects of non-financial benefits, management costs, differential return requirements, and spatial effects become less significant. While technical and market information may be a problem for small forest management, similar information problems may be a problem for non-farmer owners of farmland, where technical and market knowledge, and production decision-making is much more complex.

The result of these characteristics may be some specialization of land management within ownership types. The forest industry and corporate owners are expected to hold only forest land since they cannot optimally employ land most suitable for farming. Rather than hold assets in agricultural land, they may hold assets in the agricultural companies or commodities themselves. The likelihood of such specialization becomes important when considering the effect of uncertainty on risk averse land owners.

This paper focuses attention on the affect of uncertainty upon conversion

decision-making by comparing models of risk-averse decision makers with decision-makers valuing the option to delay investment. The particular ownership characteristics of land owners in the South will play an important role in evaluating the ability of each model to explain some of the anomalous behavior described above. Before developing the model of land-owner decision-making under uncertainty, I discuss the affect of public policy on conversion decisions, with a particular attention to how that policy affects the uncertainty faced in different land uses.

III. Public Policy and Land Conversion

Direct policy interventions into land conversion decision-making have been principally motivated by three objectives: stabilization, promotion or reduction of agricultural output; stabilization and promotion of forestry output; and control of environmental externalities. There has been no coordination in the development of policies affecting conversion and programs are often responses to the successes of earlier programs or unintended impacts of other policy. The Conservation Reserve Program (CRP), for example, was a response to conversion of marginal land partially promoted by policies during the 1970's. In addition to programs directly promoting conversion, agricultural policy, attempting to maintain farm income levels, stabilize incomes and prices, support small farms, and promote conservation, often causes unintended conversion with detrimental public consequences. While a full analysis of the effect of agricultural policy on land conversion is beyond the scope of this paper, this section highlights some of the significant effects policy has had upon land conversion.

Forest conversion was initially promoted to provide better economic opportunities for farmers and increase agricultural capacity. Many of these efforts were too successful, creating a problem of excess capacity that necessitated a range of price policies to maintain farmer incomes. Agricultural expansion also occurred after boom periods, such as the early 1970's when sudden export growth triggered concerns about reserve adequacy and significant price increases. After growth periods, however, land converted to agricultural use did not revert back to previous natural states, leaving a persistent

excess capacity. The lack of a reversion response may be due to a conversion hysteresis, or a policy response protecting the investments into capital and land from depressed prices.

The major programs affecting farm profitability are price supports (with and without acreage reduction programs) and stabilization programs. Flood control and irrigation projects have also significantly increased the profitability of particular regions by improving land conditions (Stavins and Jaffe, 1990). The principal price supports mechanisms are government purchases of commodities when prices drop to a pre-specified support price, deficiency payments of the difference between support price and market price, and supply restrictions. The former two policies raise the expected price farmers receive, and potentially decrease the price variance, leading to increased levels of output and production capacity. Acreage reduction programs, now often required of farmers receiving price supports, require landowners to remove some acreage from production in order to be eligible for price support. The land need not be converted and may remain fallow. Stabilization programs (intended to stabilize both market prices and prices to farmers) include publicly financed storage and reserves, subsidized revenue and crop insurance, export controls, and marketing restrictions. These programs attempt to reduce the price variability on the market, and avert short-term supply shortages. In addition, subsidized insurance may increase the expected profitability of agricultural production by creating a floor on farm incomes.

Forestry programs have provided subsidies for conversion costs, management costs and some preferential tax treatment, though the funds devoted to such efforts have been significantly less and are typically more recent historically in comparison to agricultural programs (Cubbage et al, 1993). Foresters' principal concern has been potential undersupply of forest products due to limited supply response exhibited for timber stumpage (i.e. the volume of forest stock). Forestry promotion programs have tended to emphasize increased management on forest lands rather than conversion of agriculture to forests, though conversion incentives such as cost sharing have been available (Cubbage et al, 1993).

Recently, policy concern for environmental externalities, such as soil erosion, decline of surface and ground water quality, loss of wildlife habitat, and deforestation, has become significant, prompting new policy initiatives. Initial concern was for the large amount of highly erodible land converted during the 1970's, though recently the concern has expanded to include carbon sequestration and biodiversity (Adams et al, 1993; Stavins, 1995; Trexler, 1990). Government responded to the conversion of highly erodible land by providing incentives for conversion of agricultural land back to forests through the Conservation Reserve Program (CRP) and providing disincentives for future conversion of marginal land to agriculture provided by other programs. While government response was motivated by externalities, the magnitude of the problem was in large part the result of other public programs promoting agricultural production.

The CRP provides half the costs of conversion and annual rental payments if land-owners convert highly erodible lands for the ten-year contract period. To discourage conversion to agriculture, tax deductions for conversion costs were removed and the "swampbuster" and "sodbuster" provisions disqualified a landowner from participating in agricultural subsidy programs if they converted wetlands or highly erodible lands (Cubbage et al, 1993; Kramer and Shabman, 1993).

Though the CRP was significantly more aggressive than previous conversion programs, such as the Soil Bank and the Forestry Incentives Program, CRP efforts to convert agricultural lands to forests did not meet program goals. While the program intended to convert 5.6 million acres, only about 2.3 million acres (less than 40% of the initial goal) have been converted. Land owners have cited a number of reasons for not planting trees, including unsuitability of soils, desire to return lands to alternate uses after the contract period, high maintenance costs, and long waits until harvest (Trexler, 1991). Regular contact with extension agencies, however, increased the likelihood that forests were planted (Trexler, 1991).

This section has attempted to highlight several aspect of the effect of public policy on land conversion decisions. First, a number of programs and policies have attempted to directly promote conversion, though the success of some has been limited. The Conservation Reserve Program, in particular, has been much less successful at promoting

conversion than originally planned, though the exact reasons remain somewhat unclear. Second, the bulk of agricultural policies have significantly affected the level and variability of income received from use of land for agricultural production, thus indirectly (though often intentionally) affecting landowner conversion decisions. These issues become potentially important factors for trends in future conversion given the current efforts in Congress to enact broad reforms in all farm programs. Current proposals call for reduction in all support programs, particularly those directly promoting conversion (i.e. the CRP). The net effect of these policy changes on conversion and land use may be significant factors affecting the provision of environmental benefits from the land and the movement of future production and capacity to a optimal levels.

IV. Land Conversion under Certainty

The model developed here assumes dynamic, profit-maximizing decision-making by individuals[8]. The land owner maximizes the stream of benefits from land use by

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[8] A number of researchers have used slight variants of this model to analyze land use change in various contexts. The framework was originally developed by Stavins and Jaffe (1990) in their analysis of the effect of flood control projects upon the conversion of forested wetlands in the southern Mississippi River delta. Their model maximizes the flow of profitable conversions, rather than profits from all lands, but is otherwise very similar in basic structure. Stavins and Jaffe's particular innovation is its approach to dealing with unobserved heterogeneity in aggregate county-level data. Stavins and Jaffe assume a lognormal distribution of parcel quality for agriculturally feasible land across the study region. The parameters of the distribution were then estimated in the regression. The effects of flood control projects are measured as shifts and increases in the number of parcels within the distribution. This method allows the modeling of the unobserved heterogeneity of land which results in the differential response of counties to the same economic conditions.

Several studies have analyzed deforestation in developing countries by assuming the only conversion from forests to agriculture occurs. Ehui , Hertel and Preckel (1990) develop a model of deforestation in Côte D'Ivorie where the agricultural productivity is dependent upon cumulative deforestation and current period rate of deforestation. Productivity declines in cumulative deforestation due to soil erosion over time and movement onto increasingly marginal lands. Productivity increases in current period

choosing which uses (forest or agriculture) are most profitable, and when conversion between uses are best made. The basic model solves the following problem:

$$\max \int U(\pi^a_t(A_t,p^a_t,x^a_t,\chi_t) + \pi^f_t(F_t,p^f_t,x^f_t,\chi_t) - C_t(f_t))e^{-rt}dt$$

$$\text{s.t.} \quad F_t' = f_t^{9} \tag{1}$$

$$A_t' = -f_t \tag{2}$$

$$C_t = C^a_t \geq 0 \quad \text{for } f_t \geq 0$$

$$= C^f_t \geq 0 \quad \text{for } f_t < 0$$

$$f_{min} \leq f_t \leq f_{max}$$

where,

U = land owner utility

π^a_t = profits from agriculture

π^f_t = profits from forestry

A_t = acres of land in agriculture

F_t = acres of land in forestry

$p^{a,f}_t$ = prices for agricultural and forestry output

$x^{a,f}_t$ = annual costs of agricultural or forest production

χ_t = owner attributes

$C^{a,f}_t$ = one-time conversion costs

f_t = acres converted: $f_t > 0$ implies conversion of agriculture to forest

$f_t < 0$ implies conversion of forest to agriculture

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deforestation due to the nutrient boost from the ash of burned forest cover. Pfaff (1994) estimates a model of deforestation in Brazil where population is taken as an endogenous variable. Parks and Murray (1994) analyze land use changes in the Pacific Northwest.

[9] The expression F_t' represents the change in F_t with resect to time.

f_{max} = maximum rate of conversion of agriculture to forest

f_{min} = maximum rate of conversion of forest to agriculture

r = personal discount rate

The land owner maximizes the flow of profits from agriculture and forestry activities. Profits are a function of current prices, input costs and the quality of land. The decision to convert is affected by the costs of conversion, which may be non-linear in the amount converted, and future prices and costs. Profits from each use depend on the amount of land devoted to each use, economic price variables, owner attributes (such as technical knowledge), and land quality. It is assumed that the land owner rationally chooses parcels of land, choosing to convert to agriculture first those parcels of the land with the highest relative profitability[10]. This cost function has a peculiar form to account for the symmetry in the direction of the conversion decision. When land is converted from agriculture to forests, f is positive and costs are C^f, whereas when conversion occurs in the other direction, f is negative and costs are C^f.

The problem is solved through basic optimal control methodology. The current value Hamiltonian is (dropping the time subscripts):

$$H = \pi^a(A,p^a,x^a,\chi) + \pi^f(F,p^f,x^f,\chi) - C(f) + \lambda^f f - \lambda^a f$$

where λ^f and λ^a are the shadow prices or marginal values of an additional acre in forestry and agriculture, respectively. By the maximum principle, the solution must maximize the Hamiltonian, with first order conditions:

$$-\partial H/\partial f = -\partial C/\partial f + \lambda^f - \lambda^a = 0 \qquad (3)$$

[10]An additional assumption about land quality must also be made. Either productivity of forestry and agriculture must both be monotonic in some common quality indicator, or the assumption of convexity of the production functions with respect to additional units of land must be relaxed. The first assumption is reasonable, though probably not universal, and the second may create problems in the analysis, particularly of uncertainty under risk aversion. As a result of the first assumption, conversion in one direction only occurs during any given period.

If these first order conditions are not met, then conversion will proceed until they are achieved. When costs are linear in f, (i.e. $\partial c/\partial f = c$, where c is constant) then a "bang-bang", or most rapid, approach path will be taken, such that:

$$
\begin{array}{llll}
f = f_{max} & \text{if} & \partial H/\partial f > 0 \text{ and } \lambda^f > \lambda^a, & \\
f = f_{min} & \text{if} & \partial H/\partial f > 0 \text{ and } \lambda^f < \lambda^a & \text{(Note, } f_{min} < 0) \\
f = 0 & \text{if} & \partial H/\partial f < 0 &
\end{array}
$$

These conditions say that the landowner will continue to convert land as quickly as possible (i.e. at a rate f_{max} or f_{min}) so long as the marginal value of additional acres in one use exceeds the marginal values in the other minus the marginal conversion costs. The marginal value of an additional acre, λ_i, represents the current value of the flow of all future benefits from an additional acre in either forest or agriculture. When the marginal cost of conversion ($\partial C/\partial f$) is greater than the difference in shadow prices, then no conversion occurs.

It is important to note the hysteresis caused solely by the presence of conversion costs. Land may not be held in its most profitable usage, since the increased output from converting the land to that use may not warrant the conversion costs. Thus, the land use of a particular parcel depends on the history of earlier economic conditions and conversion decisions. The result is a hysteresis gap in the relative profits (forestry to agriculture) necessary to induce conversion. Without conversion costs, land is converted whenever relative profits rise above or fall below unity. With conversion costs, however, the threshold relative profit necessary to induce conversion increases for each use in the opposite direction, creating a gap where no action is taken (see Figure 1(a)).

When the first order conditions hold, the solution is determined by the adjoint conditions which dictate that the rate of change in the Hamiltonian with respect to the stock must be equal to the rate of change in the shadow price. The landowner will thus

insure that:

$$\lambda^a_t{}' - r\lambda^a_t = -\partial H/\partial A_t = -\partial\pi^a/\partial A_t \text{, and} \tag{4}$$
$$\lambda^f_t{}' - r\lambda^f_t = -\partial H/\partial F_t = -\partial\pi^f/\partial F_t. \tag{5}$$

Given stock constraints (1) and (2) and equation (3), the following two equations describe the landowners decision to convert:

$$r\,(\lambda^f_t - C_t(f_t)) = \partial\pi^a/\partial A_t + \lambda^a_t{}' \quad \text{for } \lambda^f_t > \lambda^a_t\text{, and} \tag{6}$$
$$r\,(\lambda^a_t - C_t(f_t)) = \partial\pi^f/\partial F_t + \lambda^f_t{}' \quad \text{for } \lambda^f_t < \lambda^a_t. \tag{7}$$

Substituting (4) into (7) and (5) into (6), leads to:

$$\partial\pi^f/\partial F_t - rC_t{}'(f_t) = \partial\pi^a/\partial A_t + \lambda^a_t{}' - \lambda^f_t{}' \quad \text{for } \lambda^f_t > \lambda^a_t\text{, and} \tag{8}$$
$$\partial\pi^a/\partial A_t - rC_t{}'(f_t) = \partial\pi^f/\partial F_t + \lambda^f_t{}' - \lambda^a_t{}' \quad \text{for } \lambda^f_t < \lambda^a_t, \tag{9}$$

The condition in (8) states that for conversion to occur, the annualized value of the land in forests net of annualized marginal conversion costs (the LHS), must equal or exceed the annualized return to agriculture plus the capital gains in agriculture (the RHS).

The ability of this model to explain land owner decision-making may be limited by a number of factors described fully in Section 2, such as access to technical and market information, existence of perfect land markets, and non-financial landowner benefits. The following sections further develop the effect of uncertainty upon decision-making by comparing models of risk averse land owners and sunk investment.

V. Models of Uncertainty

Two models of uncertainty are developed which represent both different behavioral characteristics and different forms of uncertainty. The first model assumes a risk averse land owner faces uncertain profits from both forestry and agriculture. Profit

per acre has a fixed distribution with constant mean and variance. The risk averse land owner gives a premium to diversifying the land portfolio in forest and agriculture to reduce the variance of the return from the total land asset. The second model assumes a risk neutral land owner[11] who faces stochastic average revenues per acre following a random walk, or Wiener process. In this case, the average incremental change in revenues is constant each year with the expected profit changing each period due to the persistence of change in profits. Behavior is changed since the land owner gives a value to the option to wait to observe the level of future revenues.

The type of uncertainty considered here is uncertainty in the outcome of future events, and not uncertainty over the current state, such as prices, costs or land productivity. In each period, the land owner learns unknown prices and costs but is still uncertain about future events. Further, the revelation of more events does not improve the land owners understanding of uncertainty. The distributions of profits and prices in each model are known with certainty.

Risk aversion with uncertain profits

In this section I summarize the results of Parks (1995) who develops a model of land conversion under uncertainty. He contends this model may explain much of the observed land owners conversion decisions, particularly the lack of response to seemingly profitable conversion options. Parks (1995) takes the previous model and considers the state where future profits are uncertain, but have a known distribution, such that profits are now:

$$\pi^a(A,p^a,x^a,\chi) = \nu_a(A,p^a,x^a,\chi) + A\epsilon_a(p^a,x^a,\chi)$$
$$\pi^f(F,f^a,x^f,\chi) = \nu_f(F,p^f,x^f,\chi) + F\epsilon_f(p^f,x^f,\chi)$$

[11] A risk averse land owner could be assumed, though at the cost of significant complexity in the model.

with $E(\epsilon_a) = 0$ $\quad E(\epsilon_f) = 0,$

$E(\epsilon_a^2) = \sigma_a^2$ $\quad E(\epsilon_f^2) = \sigma_f^2$ $\quad E(\epsilon_a \epsilon_a) = \sigma_{af}^2.$

The landowner, no longer certain of future profits, maximizes the expected value of future profits,

$$\max \int E\{U(\pi^a(A,p^a,x^a,\chi) + \pi^f(F,p^f,x^f,\chi) - C(f))\}e^{-rt}dt$$

with the same previous restrictions. Note that only profits are considered uncertain and not the costs of conversion or the rate of land conversion, which is controlled by the land owner. Uncertain profits can be the result of changes in input or output prices or yield variability due to weather or uncertain future technology. Technologies, such as irrigation and drought or pest resistant crops, may reduce the variability of profit, but are not considered here.

The problem's solution is similar to the previous derivation and will not be repeated. The principal difference is that where ever profits appear in the adjoint conditions (equations 4 and 5), expected profits are substituted. Equating the adjoint conditions, the landowner compares the expected net benefits of conversion (future profits in the new use less conversion costs) against the foregone profits of the current use. Using a second order Taylor-series approximation for marginal utility $U'(\cdot) = U_m'(\cdot) + U_m''(\cdot)\,[A_t\epsilon^a(p^a_t,x^a_t,\chi_t) + F_t\epsilon^f(p^f_t,x^f_t,\chi_t)]$, where U_m' and U_m'' are evaluated at the mean returns, the land owner's criteria for conversion from agriculture to forests are modified as follows[12]:

$$\partial v_f/\partial F - rC = \partial v_a/\partial F - [U''(\cdot)/U'(\cdot)]L(s_f\sigma^2_f - s_a\sigma^2_a + (s_a - s_f)\,\sigma_{af}) - (\lambda_f' - \lambda_a')/U'(\cdot)$$

where L is the total land area, and s_{ft}, and s_{at} are the share of land in forestry and

[12] The corresponding equations for conversion from forestry to agriculture are not developed, though are symmetrical to those for conversion from agriculture to forests.

agriculture respectively.

This decision rule can be compared to the equations (8) and (9) developed under certainty. Under certainty, only the net present value of returns from alternative uses and the capital gains have been taken into account. The modified equation reflecting risk aversion includes a risk premium term (the second term on the RHS) to reflect the benefits of minimizing the variance of the overall returns from all land. The owner's land base is like a portfolio with two different assets, where the amount of each asset depends upon its individual variance and the covariance with the other use[13]. Thus, for a farmer, holding some land in forests may act as a hedge against the risks of agricultural production, such as changes in price or uncertain yields. Note that compared to the decision rule under certainty, the risk modified allocation of land to agriculture and forestry may lead to either more or less land in forests, depending on the sign of the term $[s_f \sigma_f^2 - s_a \sigma_a^2 + (s_a - s_f) \sigma_{af}^2]$. The size of the premium is proportional to $-U''/U'$, or $-V$, which is the Arrow-Pratt absolute measure of risk aversion. For risk averse individuals, $V < 0$.

There are a number of simplifications to this model affecting its ability to describe landowner behavior. First, the model assumes that the landowners stock of land is fixed and the owner only controls whether the land is in forest or agriculture. In reality, the owner has the ability to sell the land, which may be particularly relevant if there are other users with different characteristics (technical and market knowledge, and other land holdings) who can more profitably utilize the resource. Forest industry owners, for example, will not likely hold land suited for agriculture for which they have limited knowledge, and is better employed by farmers with the necessary technical knowledge. Thus, specialization in technical knowledge leads to specialization in the uses individual owners make of their land. Second, the model assumes that the entire land owners asset

[13] The mean and variance of the agricultural prices is for some optimal mix of crops based on yield and price distributions, and appropriate to the regional land and weather characteristics.

portfolio is only in land. In practice, all owners will have much more diversified portfolios such that the covariance of the forest or agricultural use with the remainder of the portfolio may be relatively small. Portfolios are likely to be large for all industry, corporate and large private investors. Even farmers, however, are likely to diversify their assets significantly. Further, many owners may prefer to hold assets in forest or agricultural sector companies rather than the land resource itself to take advantage of differences in technical knowledge. This may be particularly true for agricultural land, where technical knowledge is critical to optimal usage.

Farmers may also reduce crop income variability by using futures markets or options. Futures allow the farmer to sell (buy) crops at a future date for a fixed price, while options give the option to sell (buy) at a fixed price at any point within a specified time period. Futures and options allow the farmer to get a fixed or minimum price for future production, thus reducing the impact of future price uncertainty. Farmers, however, generally do not take advantage of futures and options because of a lack of understanding of how they operate (Hallberg, 1992). A number of other factors also limit their ability to protect farmers from uncertainty. No futures markets exist for many commodities, and even fewer options are available on commodities. Futures markets only extend for 12 months and options are available for at most 18 months (Hallberg, 1992). Options for forest products are even more limited, and may not be practical for most users with relatively sporadic harvests. Futures and options, however, provide some protection from price uncertainty and thus reduce the variance of future profits from crop production.

These qualifications suggest that diversification of the land portfolio may not be a significant factor affecting land use decision for some types of ownership. One would not expect diversification to significantly affect the forest industry, corporate owners, or large individual owners, since these owners either have specialized knowledge of one use or broad portfolios of assets, where one expects the covariance of individual investments with the entire portfolio to be small. About 58 million acres, or roughly 35%, of land is owned by the forest industry, with specialized knowledge, and corporations, with large portfolios (see Table 1). The remaining 15% of landowners with more than 1,000 acres

of forest land are also expected to have assets enough to allow significant diversification (see Table 2). While diversification may affect the decisions of farmers, the ability to use futures and options may reduce much of the need to protect themselves from uncertainty. Thus, diversification of the forest/agriculture portfolio may not be a significant factor affecting aggregate conversion decision, and may not provide a explanation for the large number of unexploited, profitable conversion opportunities.

Sunk investments under stochastic prices

A land owner determining whether to convert a parcel of land must decide if the costs of conversion and foregone profits from the old use are less than the future profits from the new use. Under certainty, this calculation can be made without error, so the decision is always clear. Under uncertainty, however, even a risk neutral land owner facing a positive net present value for a conversion investment may be unsure whether future prices and yields will continue to be favorable to that use. Further compounding the problem, the decision to convert is essentially irreversible, since the converted land may only be returned to its old use with additional conversion costs. The initial conversion costs are therefore (literally) sunk and cannot be traded, as investment in a piece of machinery might be. If a land owner is able to delay making the sunk investment indefinitely, he/she may choose to wait until conditions clearly favor the potential new use. By valuing the option to delay conversion the land owner effectively increases the necessary benefit-cost ratio to induce conversion. This section develops a model of production under stochastic prices where conversion between uses requires a conversion cost. The model is based closely on Dixit's model (1989) of intersectoral capital reallocation, and only a sketch of the derivation is provided here.

I will assume much of the same model to this point, except that uncertainty is now over average revenues per acre for agriculture (R_a) and forestry (R_f), which follow wiener processes (i.e. random walk) with geometric Brownian motion:

$$dR_a/R_a = \mu_a dt + \sigma_a dz_a \quad (10)$$

$$dR_f/R_f = \mu_f dt + \sigma_f dz_f. \quad (11)$$

dz is the increment of a standard Wiener process[14], such that:

$$E(dz) = 0 \qquad E(dz^2) = dt.$$

(12)

Average revenues might be more fully expressed explicitly writing by price and yield components, such that, R = YP. Each of these variables may also follow a stochastic processes,

$$dY/Y = A_y dt + S_y dz \qquad dP/P = A_p dt + S_p dz,$$

such that a change in revenue is equal to,

$$dR/R = (A_y + A_p + S_y/Q + S_p/Y)\, dt + (S_y + S_p)\, dz.$$

Assuming prices follow a Wiener process is a standard assumption, though representation of yields as a Wiener process requires more explanation. Uncertainty in annual yields principally derives from weather fluctuations and changes in technology. Weather fluctuations are not reasonably modelled as a Wiener process, since deviations around a fixed mean are expected. Changes in technology, however, might be modelled as a Wiener process with a positive trend since technical change is a mostly cumulative

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[14] A Wiener process must satisfy two important conditions. First, $dz = \epsilon_t (dt)^{1/2}$, where ϵ_t is standard normal random variable with mean 0 and standard deviation 1. This leads to the two conditions in (10). Second, ϵ_t is serially uncorrelated, or, $E(\epsilon_t \epsilon_s) = 0$, for all $t \neq s$. This leads to the property that the Wiener process is a Markov process, with probability distribution dependent only on the current state, and has independent increments, i.e. the probability of a change in the process is independent across non-overlapping intervals.

process. The above formulation assumes technical change is exogenous since it is unaffected by changes in prices. A fuller development of the problem would allow for endogenous technological growth, such that yields is a function of inputs (x), technology (T) and a stochastic (non-wiener process) weather term (e):

$$Y = f(x, T, e)$$

where, $T = g(w, v)$,

$dv = s_T(v)dz.$

Here, technology is a function of effort into technical change, w, and a stochastic, wiener process term, v, with standard error, $s_T(v)$, and no trend. In this model, however, I assume technological change will not be endogenous which is consistent with either exogenous stochastic change or certain change ($S_y=0$).

The random process for each interval can be expressed as a relative revenue R, where $R = R_f / R_a$, such that:

$$dR/R = \mu dt + \sigma dz \tag{13}$$

where, $\mu = \mu_f - \mu_a + \sigma_a^2 - 2\rho\sigma_a\sigma_f$, and

$\sigma = \sigma_a^2 + \sigma_f^2 - 2\rho\sigma_a\sigma_f.$

This is derived by substituting the average revenue processes (11) and (12) into Ito's Lemma for R[15]:

$$dR = R_a dR_a + R_f dR_f + \tfrac{1}{2}R_{aa}(dR_a)^2 + \tfrac{1}{2}R_{ff}(dR_f)^2 + R_{af}(dR_f)(dR_a),$$

where subscripts on the R's denote partial derivatives with respect to R_a and R_f.

[15] See Hassett and Metcalf (1992) for a more explicit description of the derivation.

The persistence of one-time shifts in revenues that result from this wiener process is central to the value of the option to wait. Because each change is an independent increment, upward and downward shifts permanently affect future expectations of revenues. This differs from uncertainty of future agricultural yield due to stochastic weather conditions which, as noted above, would not reasonably be modelled as a wiener process, since one expects annual yields to be independent and variation from mean yields not to be reflected in subsequent years[16].

The landowner decides how much land to hold in agriculture and forestry by maximizing the total expected rate of return on the land asset. This can be expressed as a combination of the current period total revenues and expected capital gain, [TR + E(dV/dt)], where TR(A,F) is the net total revenue function and V(A,F) is the asset value of the land. Here, net total revenue can be defined as the sum of the profits from each land use, $\pi_a + \pi_f$, though it will be constructive to rewrite this in a form RG(F) + H(A), where G and H are total productivity indices for the output level of forestry and agriculture, respectively. Total revenues are expressed using the relative average revenue per acre ($R = R_f/R_a$) for forestry and making agricultural price the numeraire. The linear functional form is not overly restrictive since the two productive activities are relatively independent. Over a period where the combination of land and forests remain constant, the expected capital gain can be expressed by Ito's Lemma:

$$E(dV) = V_R R\mu dt + \tfrac{1}{2} V_{RR}\sigma^2 R^2 dt.$$

The condition for the land to be willingly held in its current combination of land and forests is that the rate of return from the land asset be equal to the assets value times

[16] Yield uncertainty not modelled as a wiener process would fit into the framework of section 5, with $E[\pi]$ replacing $[\pi]$. Thus, unless the mean differed from the expectation, or the land owner was risk averse, no change from the certain case would be expected. Intuitively, there is clearly no value to the option to wait if no information is gained from future yield revelations. This might not be the case if there was uncertainty over converted land productivity, which diminishing over time as it is used.

the social rate of discount, i.e. what could be obtained by selling the asset and putting the money in the bank. This results in the differential equation:

$$TR(A,F) + V_R(A,F)R\mu dt + \tfrac{1}{2} V_{RR}(A,F)\sigma^2R^2dt = rV(A,F),$$

where r is the social rate of discount. The solution to the differential equation is (those seeking greater depth should consult Dixit(1989)):

$$V(A,F) = B(F)R^{-\alpha(r,\mu,\sigma)} + D(A)R^{\beta(r,\mu,\sigma)} + Q(A,F),$$

$$\text{where } Q(R,M) = E[\int TR(R_t,A,F)e^{-rt}dt] = RG(F)/(r-\mu) + H(A)/r,$$

B(F) and D(A) are arbitrary functions, and $-\alpha(r,\mu,\sigma)$ and $\beta(r,\mu,\sigma)$ are complex functions, the exact form of which are presented in the appendix, with $-\alpha<0$ and $\beta>1$. The solution has an intuitive interpretation which indicates how the asset's value is different from typical net present value calculations. Q(A,F) is the value of the land asset held in its current forest/agriculture distribution forever. The first two terms, $B(F)R^{-\alpha}$ and $D(A)R^{\beta}$, are the value of the option to converting land to agriculture and forestry, respectively. This option includes both the option created by continuous trends in relative prices, μ, and the value to delaying the conversion decision.

For intervals where conversion occurs, another set of conditions must be utilized. These are the value matching and smooth pasting conditions, represented below for the necessary price to switch from agriculture to forestry:

$$V(R_F,F+1,A-1) = V(R_F,F,A) - C^A(A,F)$$

$$V_R(R_F,F+1,A-1) = V_R(R_F,F,A) - C_R{}^A(A,F),$$

where C(A,F) is the cost of conversion of one unit of land from agriculture to forest. The value matching condition insures that the difference in the value of the total land

asset with and without the additional conversion is equal to the conversion costs. The reasoning behind the smooth pasting condition is more subtle. Compare a second order, Taylor approximation of V for curves with a kink (i.e. discontinuous derivative) in the curve and those meeting the smooth pasting condition (i.e. continuous). If smooth-pasting did not hold, then the asset value could be raised by converting an increment more of additional land in the direction of the steeper slope (see Dixit and Pindyck (1994), pp. 130-2 for a heuristic discussion).

Using these conditions for conversion from forestry to agriculture and agriculture to forestry, four equations can be developed to solve for the four unknowns R_F, R_A, B(F) and D(A). The equations are relatively complex and presented in the appendix. A closed form solution does not exist for the system, so numerical methods must be used. Such simulations are presented in Section 6.

The model of sunk investments under stochastic prices provides a potentially useful explanation to much of the observed "irrational" behavior of land owners who do not act on profitable conversion opportunities. The model indicates that the standard net present value calculation will over-estimate the amount of conversion that will occur, since valuing the option to wait will cause many owners to delay investments until prices clearly indicate the investment will be profitable. Such hesitation for marginal investments appears a natural response given the uncertainty over future economic conditions. While such behavior may seem natural, the degree to which it actually affects investment decisions is unclear. Since land owners clearly do not perform the complex calculations made in the model, the exact degree to which individuals delay investment may largely be a function of past experiences and the individual's previous learning opportunities in similar decision-making situations. Therefore, we might expect financial officers to better value the option to delay investments than a small land owner's ability to decide when to convert a piece of land. The actual effect of this model is therefore an empirical question which remains unanswered.

VI. Simulations of sunk conversion investment under uncertainty

Simulations were run of the models of sunk conversion investment under uncertainty to assess the magnitude of the impact given typical conditions facing land owners in the South. The simulations involved solutions to the simultaneous equations defined by the value matching and smooth pasting conditions (see appendix for equations). Since a closed form solution is not possible, non-linear programming was used to solve the equations for particular values. Simulations were performed for land owners in both soybean and cotton intensive regions. Some regions are highly dominated by these crops, such as Louisiana, where soy production is very prevalent (Kramer and Shabman, 1993). In addition, the two crops represent different degrees of future uncertainty potentially facing land owners.

Data on returns from agriculture and forestry were obtained to determine the typical trend and variance in the relative revenues of different uses. Time series of prices and yields were used to determine the annual change in average gross revenues[17]. Real prices were used to remove the effects of variation in inflation over time. Availability of cost data was inadequate to measure the trends and variances of average net revenues, so average gross revenues were used. Returns from particular pieces of land depend highly upon the specific land quality. The simulations used low values of $60 per acre and high value of $120 per acre annual return. Conversion costs are highly variable as well. A base figure of $480 per acre was used for conversion from forests to agriculture, and an estimate of $120 per acre was used for conversion from agriculture to forests. This latter costs may be an overestimate, since USDA (1988) indicates that the costs of establishing forest on agricultural land may often be less than establishment costs after harvest. A real discount rate of 2.5 percent is assumed.

The simulations are intended not as the optimization of the specific conditions of

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[17] Most statistics use time series from 1950 to 1992. Whether historical data represent true variance, and over what period such statistics are to be measured seems an open question, since there is some variance in the historical trend and variance estimators over different time periods.

some owners, but merely to exhibit the effect of the option to delay investment upon the threshold revenues necessary for land conversion[18]. Simulations may provide some indication of the likelihood that the option to delay conversion accounts for some of the observed unexploited conversion opportunities. The trend and variance statistics for timber, soybeans, cotton and rice are listed in Table 4. Data on rice is included to provide comparison to another principal crop in the south. Timber has shown slight real growth over time, with a moderate level of variance. Variances for timber does not account for the option to delay harvest which would in practice further reduce the variance. The option to delay harvest is not available for crops since they must be harvested at particular points in the season. Storage of crops, however, may provide some potential to delay crop sale, though at an additional storage cost. The affect of storage on crop revenue means and variances are not considered either. Soybeans has shown positive growth in prices with high variance, while cotton has shown a slight decline in real price with a small variance. Table 4 also shows the trends and variance in the relative revenues for different uses. In both cases, the relative revenue has a positive trend, though the trend is much larger for soybeans. The variances of the forest/soy price is much larger than the variance for the timber/cotton.

Simulations indicate that effect of the option to delay investment is much more significant effect for the conversion of forests to agriculture than the conversion of agriculture to forests. Table 5 shows the results for the simulations with soybeans as the agriculture option. The rows R^H and R^L represent the threshold relative revenues for the conversion of agriculture to forests, and forests to agriculture, respectively. The threshold prices resulting from a basic net present value calculation, R^+ and R^-, are given to show how the option to delay expands the hysteresis gap caused by the conversion costs. The increase in the gap is much larger for the forest to agriculture conversion mostly because of the positive trend in relative revenues. When future prices are likely to increasingly favor forests, a higher immediate revenue will be required to warrant conversion from forests to agriculture compared to conversion in the

[18] Dixit (1989) performs similar simulations for generic values.

opposite direction. The effect of the change in the land productivity indices on threshold revenues is indicated in Table 5. As the quality of land increases in favor of forests, a higher price is demanded for conversion to agriculture, and a lower price for conversion to forests. Table 6 shows the effect of changes in the variance and conversion costs upon threshold revenues. As expected, increases (decreases) in relative variance lead to a larger (smaller) hysteresis gap, and lower conversion costs lead to a smaller hysteresis gap.

Results of the simulations for cotton in Table 7 show that with lower variance and lower trend that the hysteresis gap is more centered about the NPV thresholds and smaller. Sensititivity analyses were performed for changes in the variance of future cotton revenues. Increasing the variance of the cotton revenues leads to increases in both the trend and variance of the timber/cotton relative revenue, as shown in Table 7. Increasing the variance leads to an increase in the threshold for conversion of forest to agriculture, but has no significant affect of the threshold for conversion of agriculture to forest, since the affects of the increasing trend and variance offset each other[19].

The results of the cotton simulations indicate that the option to delay investment may not significantly increase the existing hysteresis constraining landowner conversion decisions, particularly for conversion from agriculture to forest This conclusion, however, depends largely upon the positive relative revenue trends for both crops considered.

VII. Effects of uncertainty on policy

The models described in this paper indicate that land owners faced with uncertain future profits may make significantly different conversion decisions than owners faced with perfect information. The implications of these differences may be significant for policy attempting to promote conversion or affecting conversion decisions as an unintended outcome of other agricultural policies. In reality, expected behavior is likely

[19] This assumes all other terms, such as σ_{af}, remain constant, which may not always be true. This issue will be discussed later in Section 8.

the result of some combination of both risk aversion and valuing the option to wait since the two reactions are not mutually independent. A more general model of a risk averse land owner making sunk investments under stochastic profits could have integrated both responses, though at a cost of clearly understanding their differences and analyzing the likelihood of different ownership types exhibiting each type of behavior. The degree to which each effect is present depends upon the risk aversion of the individual decision makers, and the degree of which investments are sunk and the decision to invest can be delayed. This section analyzes the policy implications of landowner responses to uncertainty, and whether the two models lead to different implications for future policy.

Compensation for land conversion

The level of compensation required to promote conversion can be determined for both responses to uncertainty. Consider a public policy that attempts to provide compensation for landowners to switch agricultural land to forests and maintain the parcel in forests indefinitely. Now, consider only one parcel of land with particular productivity levels g and h in forestry and agriculture, respectively. The level of compensation required to induce the landowner to convert from agriculture to forestry would be:

$$W = V^{A}(R_a,A) - V^{*F}(R_f,F) + C$$

where
$$V^{A} = BR_a^{\gamma} + R_a g / (r-\mu_a)$$
$$V^{*F} = R_f f / (r-\mu_f).$$

V^{A} and V^{*F} are the asset value of the land when in agriculture and forests[20]. Here, B

[20] This derivation is similar to the binary decision problem of optimal exit and entry. See Dixit and Pindyck (1994, pp. 215-221) for a more complete derivation.

is an arbitrary constant and γ is a negative root, similar to the complex term α. The value of forests has been modified since the option to switch back to agriculture (Ap_f^{κ}) has been eliminated by the agreement to keep the land in forests. The necessary compensation for conversion is then the difference between the net present value of the old and new use plus the conversion costs plus the foregone option to switch from agriculture to forestry. If landowners are given the option to convert back to agriculture in the future the necessary compensation is reduced by the option to switch from forestry to agriculture. This analysis assumes the option to delay entering the conversion program is available. This may not be a realistic assumption for limited enrollment programs, or even open enrollment programs, since the political realities of program funding suggest that there is always the threat of enrollment closing. If enrollment cannot be delayed, then the standard net present value calculation of the expected benefits in each use is appropriate.

Under risk aversion, the costs of conversion will have to incorporate the increased or decreased cost of risk to landowners by promoting conversion from the existing optimal portfolio. To promote conversion of a particular parcel of land, the government would need to pay the difference between the marginal opportunity costs and the marginal benefits of conversion of a parcel:

$$W = \partial v_a/\partial F - \partial v_f/\partial F + iC - V L (s_f\sigma^2_f - s_a\sigma^2_a + (s_a - s_f)\sigma_{af})$$

This equation shows clearly that the expected costs of converting land of a particular quality class from one use to another will be either under or overstated if only the net present value of each use, less conversion costs, are compared. For individuals, whether costs are under or overstated depends upon whether conversion increases or decreases the risk premium for the landowners agriculture/forest portfolio. The costs of various conversion policies will depend upon how uncertainty shifts the aggregate land conversion supply curve, which is also indeterminate. After rewriting the risk premium,

it will be negative when:

$$\text{risk premium} = - V L [s_f(\sigma^2_f - \sigma_{af}) + s_a(\sigma_{af} - \sigma^2_a)] < 0, \qquad \text{or}$$

$$s_f / s_a > - (\sigma_{af} - \sigma^2_a) / (\sigma^2_f - \sigma_{af}) . \tag{14}$$

The sign of the risk affect is therefore principally a function of these variance terms which solely an empirical matter. Using the values for conversion between soybean and cotton crops and timber , (σ_{af} = .4 for soybeans and σ_{af} = .05 for cotton), gives the values of 1.33 (implying about 57% forests) for the RHS of (14) for soybeans, and .9 (implying about 47% forests) for the RHS of (14) for cotton. These results, as might be expected, center around the portfolio with equal amounts of each asset, or land use.

The effect of the irreversibility of conversion investments is to unconditionally raise the costs of promoting conversion compared to simple NPV calculations assuming enrollment can be delayed. This affect contrasts with the analysis under risk aversion, where cost might increase or decrease depending on the aggregate affects of individual owner risk premium terms. Either uncertainty response might explain the low conversion rates to forests produced by programs such as the Conservation Reserve Program. Farmers may clearly be reluctant to convert to forests, with high reconversion costs, when the option to convert to grasslands, with lower reconversion costs, is available. Farmers may also derive additional risk premiums from holding land in agriculture and thus be reluctant to convert. In both cases, conversion efforts must be aware that costs to promote conversion may differ from costs implied by standard net present value calculations.

Changes in the variance of profits and prices

The effects of changes in revenue uncertainty is particularly relevant to analyzing the effects of agricultural stabilization programs attempting to reduce price uncertainty. I therefore consider the effect of a change in the revenue variances on the likelihood to

convert. Change in the rate of conversion f with respect to revenue variance can be determined by analyzing $\partial f/\partial G \ / \ \partial G/\partial\sigma$, where G is the implicit optimal conversion function determined by setting marginal benefits of conversion minus marginal costs equal to zero. Since $\partial f/\partial G$ is always negative by the second-order conditions for profit maximization, analysis of the partial derivative of implicit function G with respect to σ is adequate to determine the sign of the effect of changes in price variance on rate of conversion. Using the implicit conversion function G, the partial derivatives of G with respect to σ_a and σ_f are:

$$\partial G \ / \ \partial\sigma_f \ = \ V\,L\,[2s_f\sigma_f + (s_a - s_f)\ \partial\sigma_{af} \ / \ \partial\sigma_f]$$
$$\partial G \ / \ \partial\sigma_a \ = \ V\,L\,[\,-2s_a\sigma_a + (s_a - s_f)\ \partial\sigma_{af} \ / \ \partial\sigma_a]$$

The sign of these terms depends upon the sign of $\partial\sigma_{af}/\partial\sigma_f$ and $\partial\sigma_{af}/\partial\sigma_a$, which are both indeterminate. If $\partial\sigma_{af}/\partial\sigma_f = \partial\sigma_{af}/\partial\sigma_a = 0$, then, as expected, the conversion rate to forests is increasing in the variance of agricultural profits and decreasing in the variance of forest profits. If, however, $\partial\sigma_{af}/\partial\sigma_f \neq 0$ ($\partial\sigma_{af}/\partial\sigma_a \neq 0$), then the conversion rate to forests may actually decrease (increase) in the variance of agricultural (forest) revenues. The exact sign depends on the specific values of the proportion of land in agriculture and forestry, and the variances and covariances of revenues.

Analyzing the effects of changes in revenue variance for the case of irreversible investment is more difficult since, with no closed form solution, the comparative static analysis cannot be performed. However, the results of the simulations indicate that the revenue threshold for conversion is decreasing in the trend and increasing in the standard error of the relative revenue change. What is needed then is to determine the effect of a change in individual stochastic terms σ_f and σ_a on the trend and stochastic portion of the relative revenue change. Using equation (14),

$$\partial v \ / \ \partial\sigma_a \ = \ 2\,\sigma_a - \rho\,\sigma_f$$
$$\partial v \ / \ \partial\sigma_f \ = \ -\rho\,\sigma_a$$

Thus, the change in the relative price trend depends upon the sign of the correlation ρ and whether ($2\sigma_a > \rho \sigma_f$). For the cases of soybean and cotton,

$$\partial \upsilon / \partial \sigma_a > 0 \quad \text{and} \quad \partial \upsilon / \partial \sigma_f < 0,$$

indicating that the trend will likely increase with increased variance in agricultural revenues, and decrease with increased variance in forest revenues. Using equation (15),

$$\partial \sigma / \partial \sigma_a = 2 (\sigma_a - \rho \sigma_f)$$
$$\partial \sigma / \partial \sigma_f = 2 (\sigma_f - \rho \sigma_a)$$

Thus, the relative stochastic change is again increasing in σ_a if ($\sigma_a < \rho \sigma_f$), while it is increasing in σ_f if ($\sigma_f > \rho \sigma_a$). For both crops considered, the variance of the relative revenue term is increasing in the variance of both agriculture and forest revenues. Agricultural stabilization policies will thus tend to promote conversion of land so long as ($\sigma_f > \rho \sigma_a$) which is likely in most circumstances.

The effect of proposed reductions in price supports and stabilization programs will lead to reductions in mean revenues and increased variances in future revenues. Reductions in mean revenues clearly leads to an incentive to convert back to forests as agricultural production becomes relatively less profitable. The simulations showed that an increase in the variance (holding the trend and both forest terms constant) led to an increase in the threshold revenue necessary for conversion to agriculture. An interesting result, however, is that the threshold for conversion to forests was not affected. This suggests that farmer's ability to respond to reduced subsidies by cutting back agricultural capacity may not be limited too severely by a hysteresis effect. As noted earlier, this result occurs because increased variance in agriculture leads to both an increased trend and variance of the relative revenues, which have offsetting affects on the threshold for conversion to forests. However, changing only the variance of agricultural revenues, and holding all other stochastic terms constant, may not be an appropriate representation of the affect of changes in agricultural subsidy programs. In addition, conversion to forests may be further stimulated if land owners exhibit significant risk aversion and desire not to hold the more variable asset.

Hysteresis effects

Possibly the principal difference in the two models of behavior under uncertainty is that hysteresis of conversion is symmetrically increased under irreversible investment, but not risk aversion. As noted earlier, some degree of hysteresis exists simply due to the presence of conversion costs. The benefits of conversion must always outweigh the foregone benefits of the present use plus the conversion costs. The increase in hysteresis due to irreversible investment results because the option to wait symmetrically increases the costs of conversion decisions in both directions. In contrast, under risk aversion, the risk premium for conversion will be negative for conversion in one direction and positive in the other[21].

These effects are most easily seen through Figure 1, which represents the threshold relative price P at which conversion occurs. Without conversion costs, the threshold price for conversion in either direction is a single R^0, which increases as the productivity of land in forests increases relative to agriculture. With conversion costs, but no uncertainty, the threshold price becomes R^+ for conversion to forests and R^- for conversion to agriculture. The basic hysteresis is seen, since a rise in price above R^+ leads to reconversion back to forests though a subsequent drop below R^+ does not lead to conversion back to agriculture. Relative prices must drop all the way back to R^- for conversion to occur.

Adding uncertainty with irreversible investment lead to a further increase in the threshold price away from the basic comparison in net benefits of each use. This leads to a further increase in the range of inaction, or hysteresis gap, which is often much larger then the basic gap caused by conversion costs (see Dixit (1989) for a discussion of the magnitudes of each effect). The line R^H represents the necessary price to convert to forests, while R^L is the price necessary to warrant a conversion to agriculture. In contrast, under risk aversion, threshold prices actually decrease for the conversion

[21] See Dixit (1989) for a more thorough argument for the differences in threshold price shifts due to the two responses to uncertainty.

decision that reduces the risk cost, and the range of inaction actually stays basically constant. The line R^R represents the relative threshold price for conversion to forestry, while the line R^S represents the threshold price for conversion to agriculture.

The increased hysteresis implied by the model of sunk costs suggests that care should be taken when making policy interventions or changes to existing policy, since it may be difficult to undo any induced conversions. The risk model actually implies undoing such interventions might be more simple.

VIII. Conclusion

This paper has attempted to extend the analysis of land conversion decisions to incorporate responses to uncertainty. This preliminaty analyses suggests that uncertainty may affect land conversions in the southern United States, though it may not fully account for all observed behavior, particularly the existence of many unexploited conversion opportunities. Diversification of the agriculture/forest portfolio may not be a significant effect for land owners with specialized technical knowledge, such as the forest industry, or for owners with a large array of assets, particularly corporations and large individual owners. These owners, however, account for a majority of the acreage in the South. Valuing the option to delay investment was shown to have significant effects, but more for the conversion of forests to agriculture than agriculture to forests, since the stochastic change in future relative revenues favors the forestry option. Thus, the slowness of owners to convert land to forests may be due in part to some of the other factors listed in Section 2, such as information constraints, spatial effects, and decision-making inertia.

The analyses, however, is preliminary and numerous factors limit its scope. For example, the argument against the effects of portfolio diversification presumed behavior, such as land use specialization, which may not be empirically true. The argument against the influence of the investment irreversibility was based on empirical estimates for the trend and variance of future relative revenues which may not adequately represent the real expectations individuals hold for these variables, and are current, and not historical,

estimates. Further , the arguments do not suggest that these models (particularly the option to delay investment) do not have a pervasive influence on landowner decisions, but only that other factors may also contribute to particular observed behaviors, such as the observed unexploited conversion opportunities. There are unfortunately a number of barriers to econometrically testing each of these models. First, there is no closed form solution for determining the threshold conversion levels for the model of sunk investment. Second, testing for risk aversion is constrained by the lack of a functional form for utility, and problems separating unobserved heterogeneity in risk preferences from other heterogeneous factors, such as price expectations or land quality. In both cases, lack of data on individual land owner conversion decisions makes uniquely identifying particular models difficult.

Understanding the effect of uncertainty on conversion decisions is an important factor in understanding the changes that might occur should proposed reforms in farm policy be enacted. The reduction of price support and stabilization programs may subject farmers to increased levels of variability in profits with unclear consequences for the provision of environmental goods from the land and the ability of farm production and capacity to move to new optimal equilibria. This analysis suggests that hysteresis effects constraining the reduction of farm capacity may not be a significant concern, and increased variance of returns from agriculture may actually lead to a further abandonment of farmland beyond that caused solely by the drop in mean revenues. The consequences of these proposed reforms should clearly receive greater attention, since a large reason for their existence is the persistence of excess supply suggesting some barriers to the attainment of optimal farm capacity exist.

There are a number of implications for environmental policy. First, the beneficial effects on the environment of cutting back agricultural subsidies may be delayed as landowners wait to see the effects of policy changes on what future returns. However, even after changes in the market have manifested themselves, increases in the aggregate level of uncertainty over returns may make conversion back to forests less likely. Thus, hysteresis may lead to some land being "stuck" in an agricultural state, even though it would be more socially beneficial (and even yield higher return to the owner) in a

forested state. Second, programs providing incentives for conversion may not be significantly affected by uncertainty, particularly if the opportunity to take advantage of the incentives is not indefinitely available. Fiscal realities typically threaten the existence of such incentives, even if it is intended to be available indefinitely. Thus programs promoting carbon sequestration or biodiversity preservation through direct incentives may not be any more costly due to the effects of uncertainty.

Table 1

Areas of Timberland in the South, by Ownership Type

(thousand acres)

	1952	1962	1970	1977	1985	1990	2000	2010	2020	2030
National Forest	10,369	10,712	10,735	10,910	10,773	10,834	10,906	10,966	11,026	11,062
Other Public	6,591	6,670	6,887	6,825	7,243	7,368	7,456	7,534	7,578	7,622
Total Public	18,912	19,344	19,592	19,712	20,001	20,192	20,362	20,510	20,624	20,714
Forest Industry	33,384	35,798	38,416	40,109	42,263	42,555	42,926	43,048	43,254	43,378
Other Private: Farmer				50,872	39,692	36,147	31,665	29,484	27,993	26,990
Corporate				13,884	16,175	17,631	19,479	20,796	21,687	22,306
Other Individual				63,914	66,018	65,472	65,210	64,398	63,254	62,173
Total Private	176,090	179,669	173,690	168,779	164,148	161,804	159,279	157,727	156,189	154,845
Total	193.050	197,051	191,312	186,514	182,164	180,006	177,641	176,227	174,793	173,527

Source: USDA, **The South's Fourth Forest**

1952-85: Actual survey data; 1990-2020: projections.

Table 2

Private ownership units and acres by size class in the South, 1978

Acres	Owners		Acres Owned	
	Thousands	Percent	Millions	Percent
1-9	2,420	69.6	5.0	3.1
10-49	560	16.1	13.6	8.3
50-99	223	6.4	15.6	9.6
100-499	241	6.9	47.2	29.0
500-999	22	0.6	14.9	9.2
1,000-9,999	12	0.4	26.7	16.4
10,000+	1		39.8	24.4
Total	3,479	100.0	162.8	100.0

Source: USDA, Forest Service, The Private Forest-Land Owners of the United States

Table 3

Land Use in the South

(acres)

	1945	1949	1954	1959	1964	1969	1974	1978	1982	1987
Grazed	166625	132635	119387	83320	77135	65618	56259	52735	42700	42654
Non-grazed	48642	86730	100455	132688	139346	144023	152925	151889	146814	145556
Forests	215267	219365	219842	216008	216481	209641	209184	204624	189514	188210
Idle	12211	1365	7177	12158	14733	13494	7589	7723	7663	19460
Crops	95140	103935	88021	77638	70111	71811	77236	82137	83958	66064
All Cropland	123655	129596	120352	115728	106772	121082	119173	122744	119184	112922
Other Land	175448	164668	173435	180955	188871	180053	182419	183408	201629	209195
South Total	514370	513629	513629	512691	512124	510776	510776	510776	510327	510327

Source: USDA

Table 4

Annual Average Revenues of Various Commodities

Individual Commodities	trend	standard error
Softwood Timber (South)	0.00011	0.12
Cotton (Arkansas)	-0.0012	0.05
Rice (Arkansas)	0.011	0.25
Soybeans (Louisiana)	0.017	0.23
Relative Stochastic terms		
Timber/Cotton	0.0035	0.0163
Timber/Soy	0.0245	0.0452

trend = % annual change in price / 100

time series: timber (1950-85), soy (1951-92), rice (1953-92), cotton (1975-92)

Individual commodity statistics represent the mean annual change in real gross revenues (trend) and the standard error of that series.

Sources: USDA; Adams et. al. (1988).

Table 5

Simulation Results: Timber/Soybean

(conversion hurdle rates: future forest return/future agriculture return)

R(H)	2.13	1.87	1.61	1.35	1.09	0.88	0.73	0.62	0.55
R(+)	2.05	1.80	1.55	1.30	1.05	0.84	0.70	0.60	0.53
R(0)	2.00	1.75	1.50	1.25	1.00	0.80	0.67	0.57	0.50
R(-)	1.99	1.74	1.50	1.25	1.00	0.80	0.67	0.57	0.50
R(L)	1.09	0.95	0.81	0.67	0.53	0.44	0.38	0.34	0.30
Productivity Ratio of Agriculture to Forests	2	1.75	1.5	1.25	1	0.8	0.67	0.57	0.5
Agriculture-$/acre	120	105	90	75	60	60	60	60	60
Forests-$/acre	60	60	60	60	60	75	90	105	120
Conversion Costs ($/acre):									
Forest to Agriculture	480								
Agriculture to Forest	120								

Table 6

Simulation Results: Sensitivity Analyes for Timber/Soy
(conversion hurdle rates: future forest return/future agriculture return)

	Standard Error			Trend					
	0.1	0.045	0.025	0.0245	0.2	0.015	0.01	0.005	0
R(H)	1.26	1.09	1.06	1.09	1.10	1.12	1.14	1.19	1.26
R(+)	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
R(0)	2.00	1.00	0.80	1.00	1.00	1.00	1.00	1.00	1.00
R(-)	1.00	1.00	1.00	1.00	0.96	0.93	0.89	0.86	0.83
R(L)	0.50	0.53	0.63	0.53	0.55	0.59	0.62	0.66	0.69

Assumptions:	
Productivity Ratio of	
Agriculture to Forests	1
Agriculture-$/acre	60
Forests-$/acre	60
Conversion Costs ($/acre):	
Forest to Agriculture	480
Agriculture to Forest	120

Table 7

Simulation Results: Sensitivity Analyes for Timber/Soybean
(conversion hurdle rates: future forest returns/future agriculture returns)

	Conversion Costs ($/acre)			
Forest to Agriculture	480	360	240	180
Agriculture to Forest	120	120	120	60
R(H)	1.09	1.09	1.09	1.07
R(+)	1.05	1.05	1.05	1.05
R(0)	1.00	1.00	1.00	1.00
R(-)	1.00	1.00	1.00	1.00
R(L)	0.53	0.56	0.61	0.66
Productivity Ratio of Agriculture to Forests	1			
Agriculture-$/acre	60			
Forests-$/acre	60			

Table 8

Simulation Results: Sensitivity Analyes for Timber/Cotton
(conversion hurdle rates: future forest returns/future agriculture returns)

	Conversion Costs ($/acre)		
Forest to Agriculture	480	360	180
Agriculture to Forest	120	120	60
R(H)	1.08	1.08	1.06
R(+)	1.05	1.05	1.03
R(0)	1.00	1.00	1.00
R(-)	0.85	0.89	0.94
R(L)	0.73	0.76	0.83

	Standard Error of avg % change cotton revenues				
	0.05	0.075	0.1	0.125	0.15
R(H)	1.08	1.08	1.08	1.08	1.08
R(+)	1.05	1.05	1.05	1.05	1.05
R(0)	1	1	1	1	1
R(-)	0.89	0.89	0.89	0.89	0.89
R(L)	0.76	0.72	0.68	0.62	0.57

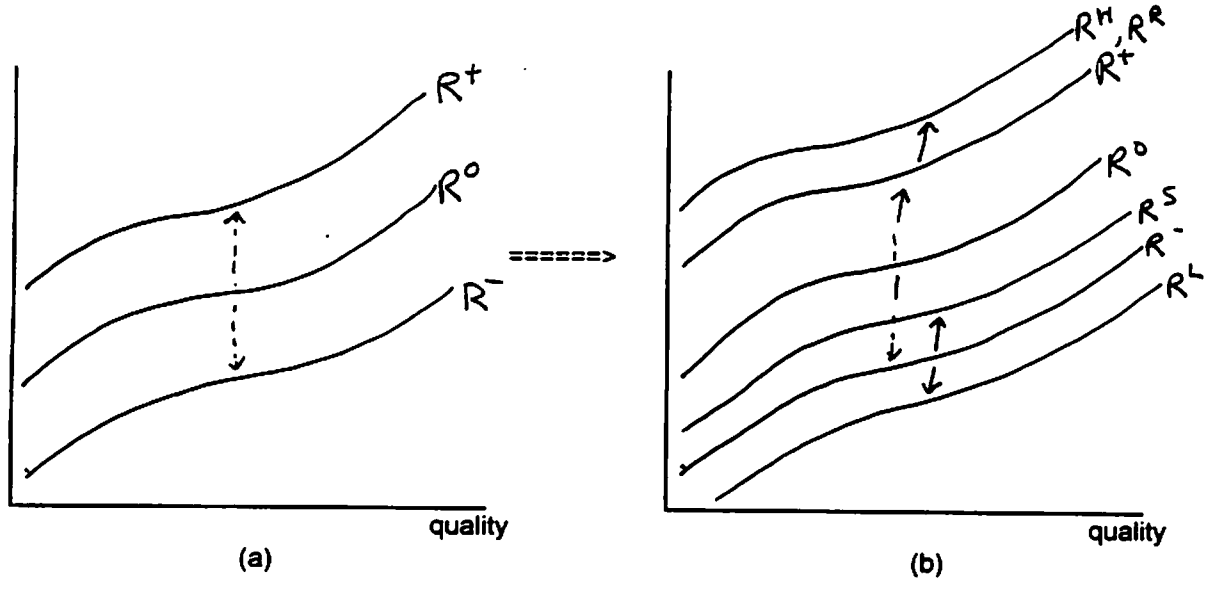
Assumptions:

Productivity Ratio of Agriculture to Forests	1
Agriculture-$/acre	60
Forests-$/acre	60

Relative revenue terms:					
trend	0.003	0.007	0.011	0.016	0.023
stand error	0.016	0.019	0.023	0.029	0.035

Conversion costs: $360 forest to agriculture
$120 agriculture to forest

Figure 1



Appendix

Intermediate terms in the calculations of sunk investment uncertainty from Section 5 include:

$$\beta = \{(1\text{-}m) + [(1\text{-}m)^2 + 4r]^{1/2}\} / 2$$

$$\alpha = - \{(1\text{-}m) - [(1\text{-}m)^2 + 4r]^{1/2}\} / 2$$

where, $m = 2\mu/\sigma^2$,

$r = 2\rho/\sigma^2$.

The result of the value matching and smooth pasting conditions are four simultaneous equations. For a current allocation of land (A,F), the four equations are:

$$bR_H^{-\alpha} + R_H{*}f/(\rho\text{-}\mu) - dR_H^{\beta} - g/\rho = C^F(A,F)$$

$$-\alpha bR_H^{-\alpha-1} + f/(\rho\text{-}\mu) - \beta dR_H^{B-1} = C_P^F(A,F)$$

$$bR_L^{-\alpha} + R_L{*}f/(\rho\text{-}\mu) - dR_L^{\beta} - g/\rho = C^A(A,F)$$

$$-\alpha bR_L^{-\alpha-1} + f/(\rho\text{-}\mu) - \beta dR_L^{B-1} = C_P^A(A,F),$$

where, $b = B(F) - B(F\text{-}1)$

$d = D(A) - D(A\text{-}1)$

$f = H(F) - H(F\text{-}1)$

$g = G(A) - G(A\text{-}1)$, and

C^A and C^F are conversion cost functions for agriculture to forestry and forestry to agriculture, respectively.

The equations are solved for b, d, R_H, and R_L.

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