Empirical Foundations for Environment-Trade Linkages: Implications of an Andean Study*

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April 1994

The Rio Summit, the Uruguay Round of GATT negotiations, and NAFTA have brought attention to the issue of trade and the environment. Will the movement towards trade and domestic policy liberalization in agriculture lead to environmental degradation? The location-specific nature of the interactions between agricultural production and the environment, and the changes in the intensity and location of production brought about by policy liberalization, suggest that the answer to this question is to be found in careful empirical research, not in stylized generalities. This study proposes a methodology for quantifying the economic and environmental impacts of trade and related policies in agriculture that accounts for the location-specific relationships between agricultural production and the environment, and illustrates this methodology in an Andean case study.

Neoclassical trade theory and its generalizations provide a link from trade to natural resource utilization in the aggregate (Kemp and Long). There is also a theoretical literature that specifically addresses the linkages from agricultural and environmental policy, through the behavior of farm firms, to environmental quality (Hochman and Zilberman, Antle and Just). These literatures demonstrate that changes in prices, technology, or policy can alter patterns of production and resource utilization that may have environmental impacts. Viewed from this perspective, the existing conceptual framework that has been developed to understand linkages between domestic policies and environmental quality can be used to understand the linkages between trade and the environment. The features of the policies may differ, but the basic economic relationships do not.

What is different about the discussion of trade and the environment from other discussions of the environmental impacts of agriculture is the unit of analysis. Trade policy analysis and quantitative modeling typically are conducted at the national level, using constructs such as the representative producer and consumer, and changes in production and resource utilization are predicted at the national level. While this level of aggregation may be useful for general equilibrium analysis, it is not useful for analysis of the environmental impacts of these

*Paper prepared for presentation at the International Agricultural Trade Research Consortium Symposium on Trade and the Environment, Toronto, June 17-18, 1994. Forthcoming in the volume, Agricultural Trade and the Environment: Understanding and Measuring the Critical Linkages, University of Minnesota Press.

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changes because the processes that govern environmental impact are location specific. Consequently, constructs analogous to the representative producer and consumer do not exist and are not considered useful in the physical and environmental sciences. For example, in the analysis of the impacts of pesticide use on ground water quality, soil scientists do not use a representative soil to predict leaching of a pesticide into the ground water of a large geopraphic region. Rather, soil scientists disaggregate the region into units of analysis with recognized soil types and other geophysical characteristics, and estimate leaching for each of these units. The only circumstance under which the leaching at each site could be meaningfully aggregated would be if water from a number of sites fed a common aquifer or flows from ground water fed a common body of surface water. From the perspective of trade policy analysis, however, environmental data at this level of disaggregation are of limited usefulness. Some way of aggregating environmental impact information is clearly needed.

This paper begins to address the problem of providing scientifically valid empirical foundations to analysis of the aggregate environmental impacts of policy changes, such as trade liberalization. Our approach is to define a common unit of measurement that can be used by the relevant scientific disciplines, including economics, to obtain valid predictions of the impacts of policy change. In the case of many agricultural applications, the unit of analysis is a farmer's field where a crop is produced. By describing the population of these units in statistical terms, and estimating impacts on each unit, it is then possible to statistically aggregate impacts to a level useful for policy analysis. In cases where it is not meaningful to characterize environmental impact using summary statistics such as the population mean, it is possible to describe impacts in probabilistic terms, e.g., as the change in the probability that a contaminant exceeds some level of concentration in air, soil, or water. It is then possible to define aggregate tradeoffs between economic and environmental outcomes in the form of a transformation frontier that is analogous to a production possibilities frontier. This transformation frontier can be used in aggregate analyses of trade policy impacts.

The next section of the paper outlines the conceptual framework at the disaggregate level where the relevant scientific disciplines can be integrated, and then describes the problems that arise in statistical aggregation for policy analysis. The remainder of the paper illustrates the use of the approach in a case study of the effects of trade liberalization on pesticide use in the Andean region. The paper concludes with some observations about the data needed to develop the empirical foundations for environment-trade linkages.

Disciplinary Integration, Aggregation, and Policy Analysis

Figure 1 provides an overview of the conceptual framework for disciplinary integration and policy analysis developed by Antle and Just. The upper part of the figure pertains to the analysis of a unit of land at the farm level. Prevailing market prices, policies, and the physical attributes of land affect farmers' management decisions in terms of both land use and input use. These decisions affect agricultural production, but also may affect the environment and human health through two distinct but interrelated mechanisms. Decisions at the extensive margin determine which particular acres of cropland are put into production. Management decisions at the intensive margin determine the application rates of chemicals, water use, and tillage practices. Physical relationships between the environmental attributes of the land in production and management practices then jointly determine the agricultural output, environmental impacts, and health impacts associated with a particular unit of land in production. Thus, the land use and input use decisions of farmers form the linkage between policy and environmental and health consequences.

Each unit of land in production has environmental and management characteristics that are functions of prices, policies, technology, and other farm-specific characteristics. As the lower part of Figure 1 indicates, the distribution of farm and environmental characteristics induces a joint distribution of input use, outputs, and environmental impacts. This joint distribution provides the basis for aggregation of the field-specific characteristics. These aggregate values can be utilized in welfare and policy analyses.

The construction of the disaggregate model begins by defining a population of land units (referred to henceforth as a field) in relation to an environmentally meaningful geographical unit, such as an aquifer or watershed. A vector ω_j represents the jth field's physical characteristics that affect both crop productivity and environmental impact. Environmental impact is represented with a stylized physical model

(1) $z_{jt} = z(x_{jt},\omega_j,\epsilon_{jt}),$

where x_{jt} is a vector of management actions taken on the jth field at time t, ϵ_{jt} is a random term representing the effects of weather and climatic variation, and z_{jt} is the environmental impact measured in physical terms per unit of land (e.g. per square meter). The function $z(x,\omega,\epsilon)$ is assumed to be increasing in x, and may exhibit certain convexity properties, depending on the type of physical process involved.

The economic model is based on the allocation of land and other inputs to maximize expected economic returns (which may be adjusted for risk attitudes in a more general presentation). All farms produce with an identical technology (more generally, the technologies may be differentiated by measurable characteristics). In the production period, the ith farmer manages n^i fields with environmental characteristics $\omega^i = (\omega_1^i,\ldots,\omega_n^i)$. The indicator function δ_{jk}^i is defined to be equal to 1 if field j is in production of crop k and equal to zero otherwise. Also let $\delta_j^i = \Sigma_k \delta_{jk}^i$ and $\delta^i = (\delta_1^i,\ldots,\delta_n^i)$. The vector of physical attributes of land in production is then $\omega(\delta^i) = (\omega_1^i\delta_1^i,\ldots,\omega_n^i\delta_n^i)$. Letting the size of the jth field on the ith farm be a_j^i, total land in production on the ith farm is $\Sigma_j a_j^i \delta_j^i$.

Production of crop k on field j is defined by $q_{jk}^i = q_k(a_j^i,x_j^i,\omega_j^i,\epsilon_j^i)$, where for simplicity the production process is represented as static. As described below, it will more generally be defined as a dynamic process. By defining suitable probability distributions for the production disturbances ϵ and for prices, the ith farmer's management problem is to maximize expected returns by choosing $x^i = (x_1^i,\ldots,x_n^i)$ and δ^i, subject to physical attributes ω^i, and price, policy, and technology parameters ϕ. The solution to this optimization problem gives the demand functions $x_j^i = x(\phi,\omega_j^i)$ and $\delta_j^i = \delta(\phi,\omega_j^i)$. Observe that these functions are discontinuous, but under reasonable conditions the discontinuity in x occurs only when δ switches from one value to the other. Otherwise, x is a conventional factor demand function.

The physical characteristics ω_j^i of fields are distributed in the population according to a distribution with parameter Θ. This distribution induces a joint distribution of input use x^i and land use δ^i in the population, $G(x,\delta|\phi,\Theta)$, for given policy parameters ϕ and for the given distribution of physical characteristics Θ. This joint distribution in turn induces distributions of the physical characteristics of land in production, crop production, and environmental impact through the relationships defined above. Thus, farmers' production decisions generate a joint distribution of land use, input, output, and environmental impact associated with the population of fields in the region. From this joint distribution, corresponding conditional and marginal distributions can be derived for these variables that can be used in policy analysis. Of particular interest for policy analysis is the joint distribution of crop production and environmental impact $F(q,z|\phi,\Theta)$. Using this joint distribution, it is possible to aggregate these outcomes for use in policy analysis.

The construction of an aggregate transformation frontier can proceed in a manner similar to the construction of a conventional production possibilities frontier. Following Stoker's analysis of statistical aggregation, and its application to production analysis by Antle, aggregate quantities X and Ω can be interpreted as mathematical expectations of the vectors x and ω taken with respect to the distribution $G(x,\delta|\phi,\Theta)$. Moreover, an aggregate environmental impact function of the form $Z(X,\Omega;\phi,\Theta)$ can be derived from G and the field-level function (1). Similarly, using the crop production functions defined above, it is possible to construct an aggregate output function $Q(A,X,\Omega;\phi,\Theta)$, where A is total land in production. The notation used here is intended to convey Stoker's basic result, that the aggregate functions are defined for given parameters of the distributions of the underlying disaggregate variables. Changes in the those distributions brought about by changes in the price and policy parameter vector ϕ, or by changes in the parameter vector Θ defining the distribution of physical characteristics in the population, induce changes in the aggregate relationships.

Two fundamental problems arise in the construction of the aggregate environmental impact function $Z(X,\Omega;\phi,\Theta)$. First, even at the field level, it is unclear how one aggregates the water quality effects of different types of chemicals. This problem could be solved if damage functions were available that expressed outcomes such as human health as a function of different types of chemical contamination. Second, as mentioned in the introduction, it is unclear whether an aggregate quantity concept is meaningful, as illustrated by the discussion of the spatial aggregation of pesticide leaching to infer regional water quality changes. One approach to resolve this problem is to interpret the variable Z as a probability statement based on the distribution function F, and then use this distribution to infer changes in contamination risks.

Interpreting Z as an indicator of environmental quality, so that social welfare is increasing in Z, the function $Z(X,\Omega;\phi,\Theta)$ should be decreasing in the elements of X. If the disaggregate function is defined so that z is increasing in ω, then Z should be increasing in Ω. The curvature properties of the field-level environmental impact function (1), and of the aggregate Z function, however, are not generally known. According to economic theory, Q is an increasing and concave function of A and X. Therefore, the aggregate transformation function between Z and Q has a negative slope, but it is necessarily concave to the origin only if Z is a concave function. Antle and Heidebrink argue that as environmental resource utilization rises, beyond some point its marginal productivity becomes negative, and therefore the slope of the transformation frontier between agricultural output and environmental quality becomes positive beyond some point, as illustrated in Figure 2. This reasoning suggests that the transformation frontier must be concave to the origin at least in a neighborhood around the point where the frontier is vertical.

The slope of the transformation frontier provides information about the opportunity cost of environmental quality in terms of forgone output. This opportunity cost reflects the degree of vulnerability of the environment to disruptions caused by production activities. This vulnerability depends on the factors embodied in the underlying distributions of physical characteristics of the land in production, the economic and technological characteristics of the farms, and the prices and policies faced by farmers. A key empirical research question is how these underlying conditions affect the environmental vulnerability and thus the slope of the transformation frontier.

Both the transformation frontier presented in Figure 2 and the neoclassical transformation frontier represent the changes in outputs that are generated by varying input use for a given technology. However, there is an important difference between the two constructs. The derivation of the neoclassical transformation frontier is based on a representative aggregate technology for each sector of the economy; the aggregation problem is ignored in the neoclassical derivation of the transformation frontier. In contrast, in the preceding derivation each aggregate function and thus each transformation frontier is defined for given values of the parameter vectors ϕ (policy) and Θ (physical characteristics of land). Therefore, changes in policies that change relative prices in the economy induce movements along the frontier as input use changes, and may also induce changes in the position of the transformation frontier in the (Q,Z) quadrant. Consequently, the distinction between movements along and shifts in the frontier may be ambiguous when policy changes occur.

In the short run Θ is taken as given, but in analyses of long-term sustainability, Θ may be time-dependent and related to past production decisions (e.g., as in the case of soil degredation over time). These dynamic considerations may also complicate the distinction between movements along and shifts in the frontier.

Changes in technology with given prices and policy parameters clearly shift the frontier. Thinking in terms of the aggregate economy, the transformation frontier between Q and Z is a two-dimensional slice of a higher-dimensional transformation surface that includes other sectors' outputs. Intersectoral changes in resource utilization in response to trade liberalization or other policy changes also should shift the frontier.

Trade and Economic Policy Changes in the Andean Region

The empirical analysis conducted in the following section is based on a case study of the environmental, health and production impacts of pesticide use in potato production in Ecuador. Ecuador and other Andean countries are undergoing policy reforms, switching from protectionist, import-substituting policies towards that set of policies associated with trade and domestic policy liberalization.

Ecuador is classified as a lower-middle-income country by the World Bank and has a rapidly growing population of 10 million. It is about the size of Georgia and Alabama combined and is divided into three distinct geographic regions: the coastal plain, the sierra and the Amazon. Population in the sierra is found in the series of inter-Andean valleys formed between the parallel ranges of the Andes.

In most of the sierra of Ecuador, the agricultural frontier has been closed. The inter-Andean valley bottoms were the traditional sites of agricultural production based on indentured labor on large farms. Valley sides were used as forest reserves or pasture. Agricultural reform broke up the large farms with the less desirable land on valley sides going to the new class of small farmers. Rapid population growth and a low technology base resulted in area expansion, principally by moving up the valley sides onto marginal land. The result is large areas of sierra crop land under risk of environmental degradation (Southgate and Whitaker). The large farms on the valley bottoms converted cropland to activities with lower labor intensity, typically pasture for dairy production. With the agricultural frontier closed, further growth in agricultural production must come from intensification of production through higher yields and shorter crop rotations.

Agricultural products are important exports for Ecuador. The traditional export crops, bananas, coffee and cacao are all from the coast. The principal sierra products of corn, beans, wheat, barley, potatoes and diary are typically for domestic consumption (Whitaker and Colyer). Though there are cross-border flows, food crops are lightly traded within the Andean region (Janssen, et al.). However, these patterns of regional trade are likely to change. Substantial investments in infrastructure have improved roads, reducing the isolation of sierra producers. In most locales, market information is rapidly disseminated by radio and by transporters and wholesalers.

The Andean Pact is a regional trade bloc that consists of the five tropical Andean countries - Venezuela, Colombia, Ecuador, Peru and Bolivia. These countries have until recently followed the import-substituting industrialization policies common in Latin America, preventing effective economic integration. In this sense, Ecuador has been similar to many other countries in Latin America; successive governments utilized overvalued exchange rates, large fiscal deficits, price controls, subsidies to major sectors, restrictive tariffs and non-tariff barriers to trade in a matrix of inward-looking, protectionist policies. Examination of these policies shows a distinct bias against agriculture, in particular the non-export agriculture sector (Scobie, Jardine and Greene; de Janvry, Sadoulet and Fargeix). Lee and Espinosa examined the effect of this policy matrix on agricultural pesticides and found an effective subsidy of 27%, mainly through the distorting effects of controlled exchange rates. Thus the Ecuadorian policy setting is similar to those of other lower-income countries documented by Schiff and Valdes.

Recently, however, the Pact established a process of trade reform, eliminating prohibitions and reducing tariffs and non-tariff barriers on a host of products, including agricultural food crops (Ramos and Acosta). The new Pact agreements, coupled with earlier reform efforts have reduced some of the biases against sierra agriculture. Responding to an improved policy environment in Ecuador, sierra producers expanded the area of potatoes and wheat, and increased milk output, reversing downward production trends for these products and recapturing domestic markets (Whitaker and Alzamora). In addition to recovering domestic markets, the regional trade reforms offer the opportunity for producers to sell into neighboring countries. Ramos and Acosta observe that relative to Peru and Colombia, Ecuadorian producers enjoy a comparative advantage in several sierra food crops.

Potato production in Ecuador is almost exclusively the domain of small farmers located on the sides of inter-Andean valleys (Figure 2). The data used in the case study were collected from a typical sierra potato-dairy production zone in Carchi Province in northern Ecuador, just on the Colombian border. Carchi has recently become the largest potato producing province in Ecuador, reflecting a trend in concentration of production in fewer locations. Improved roads reduced transportation costs to major markets and allowed production to move to more ecologically favorable areas. (Crissman and Uquillas). For the potato farmer, the fallow portion of the crop rotation is used as pasture for a mix of beef and dairy cows. Most milk in Ecuador is produced by large farmers in specialized dairies. Milk production for the small potato farmer is a supplementary activity for home consumption and occasional sale.

In addition to its ecological advantages, Carchi potato farmers traditionally have taken advantage of their frontier location to sell into both Colombian and Ecuadorian markets. Despite restrictive policies on trade, numerous observers have noted that there can be significant black market flows of potatoes in either direction due to price differences in major markets (Barsky; Crissman and Uquillas). Ramos et al. examined the comparative advantage of potato production in Carchi compared to importing potatoes from the frontier market towns of Peru and Colombia. Confirming current market flows from Carchi into Peru and Colombia, in mid-1992 Carchi enjoyed a distinct comparative advantage in potato production. Trade reform will remove prohibitions on trade in potatoes, eliminating most of the transactions costs of the black market.

Potatoes are an important staple in Andean diets. Growth of potato production in Colombia has exceeded that of other Pact countries, mirroring its per capita income growth and rapidly expanding population. In addition to uses in the traditional diet, the growth of the fast food industry has created a significant new market for potatoes in Colombia. The newly open Colombia market is thus expected to cause a significant shift in demand putting upward pressure on Ecuadorian potato prices in the short to medium term.

Seasonality of production and lack of storage due to strong consumer preferences for a fresh product mean that potato prices cycle sharply in major urban markets in the region. Andean Pact government efforts to dampen price swings have universally failed and presently there is no government intervention in the output market. With open access to both Colombian and Ecuadorian markets, Carchi producers can take advantage of different price cycles in their major markets as illustrated in Figure 3. With options to send potatoes to the better market, Carchi producers effectively reduce downside price risk, obtaining, on average, higher prices.

In addition to trade barriers, there are numerous government interventions in agricultural input and output markets. As mentioned above, an exception to the rule is the potato output market. An example of input market intervention is the study of pesticide subsidies by Lee and Espinosa where a combination of overvalued exchange rates and price controls effectively lowered the price of pesticides to farmers. The removal of these subsidies can be expected to cause pesticide price increases.

In the output market, the case of milk contrasts with that of potatoes. All the Andean Pact countries are deficit in milk production and all have milk price supports. In 1992, Colombian price supports were significantly higher than those of Ecuador and mule trains taking black market milk from Ecuador to Colombia were a common sight along the border. The support prices of the two countries are expected to converge. Whether those of Colombia will fall or those of Ecuador will rise is not clear. Regardless, for the small potato farmer of Carchi, milk production is a minor farm activity and most of any increased demand will be met by the specialized producers. Large Ecuadorian producers are rapidly improving milk yields, especially compared to the low-technology systems of the small farmers.

Trade Liberalization and the Environment: A Case Study of Pesticide Use in Ecuador

This section presents an analysis of the impacts of trade liberalization on agriculture and the environment using data obtained in a study of the economic, environmental, and health impacts of pesticide use in the potato production system of northern Ecuador. A complete description of this study is found in the book manuscript in preparation by Crissman, Antle and Capalbo. Following the approach described by Antle and Capalbo, primary production data were used to estimate econometric models that represent the farmers' decisions on the extensive (crop choice) and intensive (input use) margins. These econometric models provided the parameters for construction of a stochastic simulation model of the production system, summarized in Figure 5. The outcomes of this economic simulation model were then input into a physical simulation model to estimate environmental impact, defined here in terms of the leaching of pesticides beyond the crop root zone (Hutson and Wagenet; Wagenet, Hutson and Ducrot). These two simulation models provided the basis for construction of the distributions of land use, input use, environmental impact, and agricultural production that in turn allow the construction of the aggregate transformation frontier described above.

Potato production in the Carchi Province of northern Ecuador is concentrated in a highland zone 30 kilometers south of the Colombian border. Only half a degree north of the equator, production occurs in altitudes between 2800 and 3400 meters on steeply sloped, deep volcanic soils. There are virtually no changes in day length, little seasonal temperature variation and limited variation in rainfall. The cropping system is dominated by potatoes and pasture for dairy cattle. Because of the equatorial location and rainfall patterns there are no distinct planting or harvesting seasons, virtually all recorded planting dates are on different days, evenly distributed through the months of the year. Conditions in Carchi are highly favorable to potato production, with farmers in the sample obtaining average yields of 22 metric tons per hectare as compared to a national average of 8 MT/ha and yields of around 30 MT/ha in the United States.

Production data were collected in a farm-level survey conducted in the Carchi region on 40 farms during 1990-92. Because crops are planted and harvested continuously throughout the calendar year, data were collected for parcels, where a parcel is defined as a single crop cycle on a farmer's field. Excluding pasture, a total of 490 parcels were registered of which 338 were potato. From these a total of 320 potato parcels were used in the estimation sample. The potato fields not used had incomplete harvest data due to the local practice of selling an unharvested field to third-party harvesters. The 320 parcels in the sample represent 178 different fields.

Detailed parcel-level production data were collected on a monthly basis. Potato production in Ecuador is management intensive, and there are as many as 20 distinct operations during the six-month crop cycle. Post-harvest farmer recall of detailed data on pesticide use is unlikely to be accurate. Thus, the investment in monthly visits was deemed essential to the success of the data collection effort. See Crissman and Espinosa for further details on sampling and data collection procedures.

The late blight fungus (Phytophthora infestans) is the principal disease and the tuber boring Andean weevil (Premnotrypes vorax) and several foliage damaging insects are the principal pests affecting production. The control of these three threats require distinct strategies relying primarily on chemical pesticides.

Late blight can be a devastating disease where in a susceptible variety entire fields can be destroyed overnight. Effective control relies on prevention. Most fungicides are contact-type, killing the fungus encountered on the surface of the plant. These products are typically applied at prescribed intervals depending on the weather. During periods of rainy weather, the frequency of spraying increases as conditions for fungus development are better and the rain washes the fungicide off the foliage.

The data contain 1881 observations on fungicide applications, where the unit of observation is a day when one or more fungicides were applied. Figure 6 illustrates the patterns during the production cycle of the timing of the individual applications. The data show that most fields were treated with fungicides at least four times. The dispersion in the timing of the applications reveals a wide range of pest management behavior that presumably reflects differing physical and economic conditions faced by farmers. The quantity data reveal that the amounts applied follow the development of the foliage, with average application amounts increasing through the first several sprays and then remaining at about the same level for the remaining sprays. After plant senescence, foliage does not contribute to tuber development and farmers cease using fungicides.

Construction of the Integrated Economic/Physical Simulation Model

The economic simulation model is built from four basic components. First, as illustrated in Figure 5, are the underlying distributions of economic and physical characteristics of the fields in the study watershed. The second component is the net returns distributions of the principal crops in the rotation (potatoes and milk). The net returns distributions for potatoes was estimated using restricted Cobb-Douglas revenue and cost functions, with input prices for variable inputs normalized by expected output prices (labor, fertilizer, pesticides), and with given field size and other physical characteristics. The net returns distribution for dairy was estimated as a lognormal distribution. The third component of the simulation model is a system of dynamic factor demand equations for the three categories of pesticides used in potato production, as described in Antle, Capalbo and Crissman. The final component of the economic simulation model is a restricted revenue function used to predict the value of production, estimated with prices for labor and fertilizer inputs and with quantities of pesticides, land, and physical characteristics.

The leaching model is a simplified version of the LEACHM model designed by Hutson and Wagenet. This is a detailed process model of pesticide leaching that was parameterized with soils and other physical data collected from the study area, and simulated with a 30-year series of weather data (rainfall and temperature). The distribution of cumulative leaching beyond the root zone was found to be positively skewed, with many observations at or near zero but also with a long positive tail. This distribution was estimated using Heckman's two-stage econometric procedure for censored distributions, by defining a cutoff point below which all observations were interpreted as equal to zero, and above which all observations were interpreted as positive. The probit technique was used to estimate the probability that a positive amount of leaching occurred, as a function of weather and physical characteristics, and then the Heckman procedure was used to estimate a regression relating the quantity of leaching to weather and physical characteristics, corrected with the Mill's ratio for the probability of zero leaching.

Results of the Simulation Analysis of Trade Liberalization

As described in the previous section, trade liberalization would be expected to have two significant impacts on the commercial potato production regions of Ecuador. First, it is estimated that elimination of exchange rate distortions would indirectly increase the price of pesticides, an imported good, by approximately 30 percent. Second, the price of potatoes relative to dairy products would rise, although quantitative estimates of the magnitude of this effect are not available. Therefore, to represent the possible effects of trade liberalization on the potato/dairy production system, three policy scenarios were used relative to the status quo: an increase in pesticide prices, referred to here as a tax on pesticides, ranging from 0 to 90 percent; a potato price increase, referred to here as an output price subsidy, ranging from 0 to 90 percent; and a pesticide tax of 30 percent with a potato price subsidy ranging from 0 to 90 percent. 40 fields were sampled for each of the three policy scenarios and the four policy settings in each scenario. Each field was simulated for 10 production cycles (a cycle is one crop from planting to harvest). Each policy setting was replicated 4 times. The model thus produced 1600 observations for each policy setting. These 1600 observations form a marginal distribution of outcomes for the variables of interest. The model produces distributions for total pesticide quantity applied to a field, total number of pesticide applications, pesticide leaching and crop revenue. Changes in the location and shape of the distributions make it possible to analyze the effect of the different policy settings. Leaching outcomes were estimated for each pesticide application within each production cycle. About 30,000 individual pesticide applications were simulated in the complete analysis. Though it is possible to sample from the set of environmental characteristics, for simplicity in interpretation, the simulation experiment was conducted for one set of physical conditions deemed to be representative of the land currently in production.

All else equal, the pesticide tax scenario should reduce pesticide use and higher potato prices should increase pesticide use, and these outcomes were verified in the simulations. The third scenario in which the pesticide tax and potato price subsidy were combined is considered to be most representative of actual policy liberalization. Figures 7-10 show the simulated marginal frequency distributions of fungicide quantity, numbers of applications, leaching, and revenue distributions under the base case (30 percent pesticide tax, status quo potato prices) and the 3 levels of output price subsidy (30, 60, and 90 percent).

Recall that the model chooses between a potato crop and pasture used for dairy production. A pasture cycle receives no pesticide applications, while virtually all potato cycles are treated. Thus, the zero category in Figures 7-9 indicates the extensive margin effects on fungicide quantities, application numbers, and leaching as farmers shift from potatoes to pasture in the simulated crop rotation.

Figure 7 presents the simulated marginal distributions of the total mass of the fungicide Mancozeb in grams of active ingredient applied to each field. The imposition of the 30 percent pesticide tax reduces pesticide use relative to the status quo, but the higher potato prices have the opposite effect. The changes in the zero category show the extensive margin effects as pasture occurs less frequently in the rotation. The shift of the mass of the distribution to the right shows the intensive margin effects, as fields receive larger treatments. Figure 8 shows that the total number of applications also increases as potato prices increase.

Figure 9 shows the distributions of cumulative mass (mg/m^2) of Mancozeb leached below the root zone on each field in production. The leaching patterns are similar to the pesticide use patterns, but are not identical. It is significant that the likelihood of a positive leaching event is not in direct proportion to pesticide use. Despite the dramatic reduction in pasture, the zero category shows numerous fields without leaching, indicating that many fields received fungicide applications in amounts or under weather conditions insufficient to cause leaching. The distributions in Figure 9 indicate that the probability of a positive amount leached increases substantially with a moderate increase in the price of potatoes. Thus, the change in the total mass of pesticide entering the watershed is explained by the change in area in potatoes, the change in quantity applied per treatment, and the change in the number of treatments.

Figure 10 shows the effects of the policies on the revenue distribution in millions of Ecuadorian Sucres for the sample fields. The mass of the distributions shift to the right with higher potato prices.

Figures 11 and 12 present the aggregate data from the simulation analysis for the three policy scenarios (pesticide tax, potato price subsidy, combined tax and subsidy), with the natural logarithm of the total value of production of all fields measured on the horizontal axis. Defining M = 50,000 as an upper bound for total cumulative mass of Mancozeb predicted to leach beyond the root zone from all fields in the watershed over the 5-year period following the crop cycle during which it was applied, and defining L as the predicted total cumulative mass leached from all fields in the watershed, aggregate water quality is measured in Figure 11 as log(M-L). The vertical axis of Figure 12 measures the probability that leaching on a field in the watershed is zero, estimated as the proportion of fields in the simulation that had zero leaching. The base case (status quo) points are the four in each figure where the pesticide tax and potato subsidy scenarios coincide.

As theory predicts, the scattering of data points from the simulations imply that the transformation frontier has a negative slope, indicating the tradeoff between environmental quality and production that occurs as changes in policy induce changes in crop rotations and pesticide use. Compared to the status quo, the pesticide tax yields improvement in water quality at the cost of lower output; the increase in potato prices shows the opposite effect.

As noted in the theoretical derivation of the frontier, policy changes could induce both a movement along and a shift in the transformation frontier. Because these simulations were conducted holding constant the physical characterisics of land in production and the production technology, it seems reasonable to interpret these results as representing a movement along a stable frontier.

Viewed in this way, the results indicate that policy liberalization that increases pesticide prices by 30 percent and also increases potato prices by 0 - 90 percent would not necessarily have an adverse impact on either the environment or on agricultural production. Indeed, about half of the 16 policy simulations yield combinations of output and water quality that are in the same general area of Figure 11 as the base case. The results of the simulation also indicate, however, that because of the natural variability in both output and in the physical processes associated with leaching, a fairly wide range of outcomes is possible.

The nearly log-linear relationship in Figure 11, with both axes measured in logarithms, indicates that there is a tradeoff between output and water quality as theory predicts, but the transformation frontier is convex to the origin. Figure 12 also indicates a tradeoff that is convex to the origin. The explanation for these findings is that, as the price of potato output rises relative to dairy, the crop rotation shifts to nearly continuous potato production. Once this extensive margin substitution has occurred, the marginal impacts on water quality decline because they are caused only by increases in pesticde intensity, but potato production continues to increase in response to higher output prices. The declining ground water quality does not feed back to adversely affect production, so there is no reason in this case for the frontier to be concave to the origin as in Figure 2.

Social welfare presumably depends on both the total quantity of leaching and its probability of occurring. With an appropriate welfare metric, the outcomes in Figures 11 and 12 could be summarized functionally and included in an aggregate analysis of the welfare effects of policy liberalization.

Implications for Research on Trade and the Environment

This study proposes a methodology for establishing the linkages from the field level at which environmental impacts can be meaningfully measured and modeled to the aggregate level at which policy analysis is conducted. The methodology was illustrated with an integrated economic/physical model that links farmers' production behavior to the leaching of pesticides to ground water. The distribution of outcomes at the field level was used as the basis to statistically aggregate outcomes and represent them in the form of a transformation frontier that can be used in policy analysis. The resulting transformation frontier demonstrates the tradeoff between agricultural production and environmental quality that has been hypothesized in the economics literature. Several features of this tradeoff deserve further research from both theoretical and empirical perspectives, including its convexity properties, the effects of aggregation, and the factors that shift the frontier versus those that cause movements along it.

As the Andean case study illustrates, disaggregate analysis of the relationship between agricultural production and environmental quality can generate a large amount of detailed information, too much information to be comprehended and used in aggregate policy analysis. The aggregation of the detailed, disaggregate data into a transformation frontier provides a means to summarize the disaggregate data in a form that is valid from the point of view of the underlying scientific disciplines and also intuitively appealing to policy analysts.

The modeling conducted in this study is partial equilibrium, and needs to be linked to a general equilibrium model to predict long-term trends in relative prices that would be associated with policy liberalization. Most general equilibrium models in the literature, however, do not provide the level of detail on the agricultural sector to be useful for this purpose. There is a need for these general equilibrium models to be further disaggregated by commodity and geographically to facilitate the linkage to environmental impact analyses such as the one described in this study. This disaggregation will need to be done on a case-by-case basis, to match the particular economic and environmental relationships that are judged to be most important.

A key problem with environmental analysis is that it is data intensive. A key challenge facing researchers is to discern what level of precision is required in the disaggregate economic and physical analysis to be adequate for policy analysis at the aggregate level. Knowing the level of precision required would, in turn, define the minimum data sets that are needed to provide scientifically valid inferences for the individual land units that are to be statistically aggregated for policy analysis. We hypothesize that the solution to this challenge lies in the development of geographic information systems that integrate location-specific physical and economic data.

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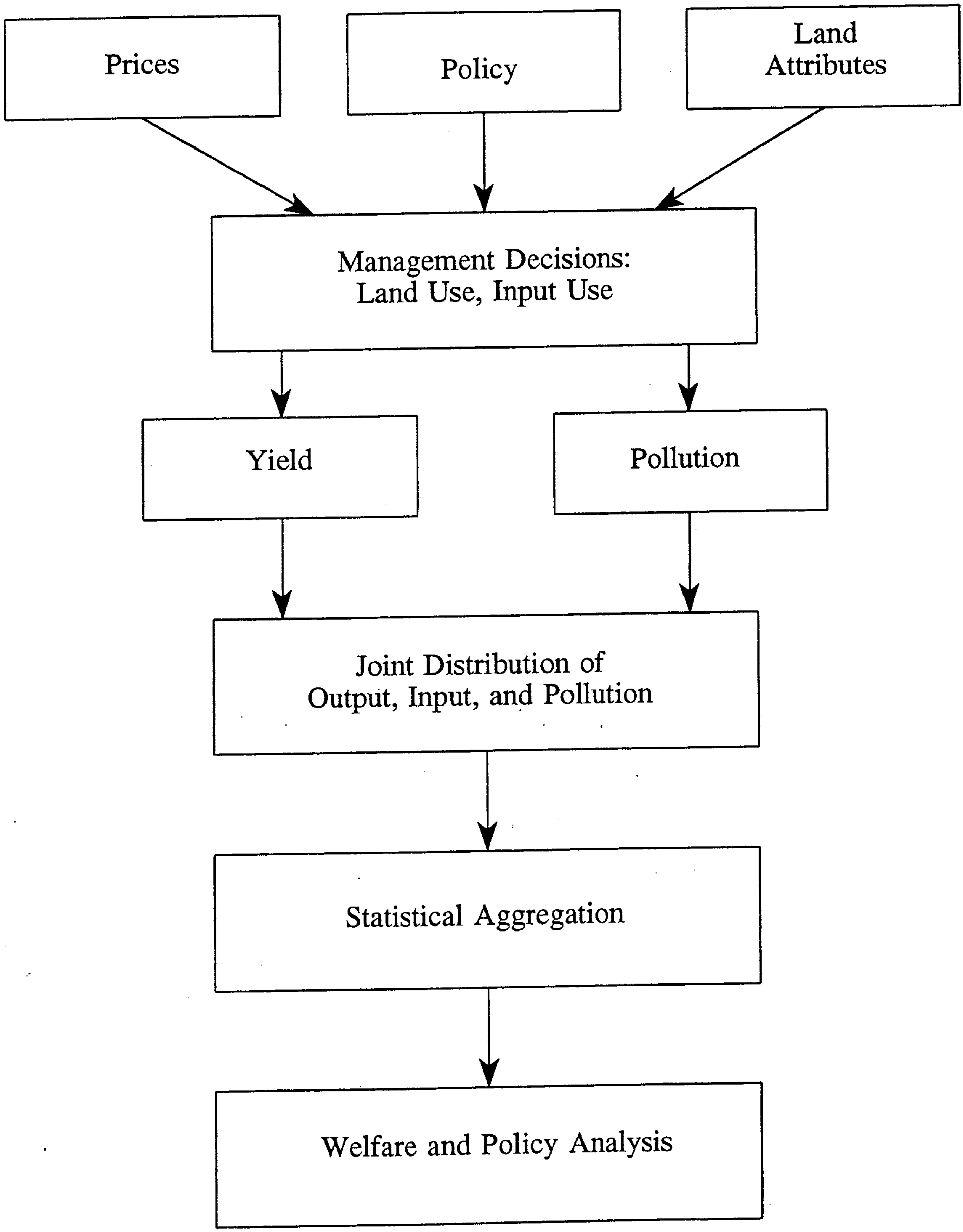


Source: Antle and Just (1991).

Figure 1

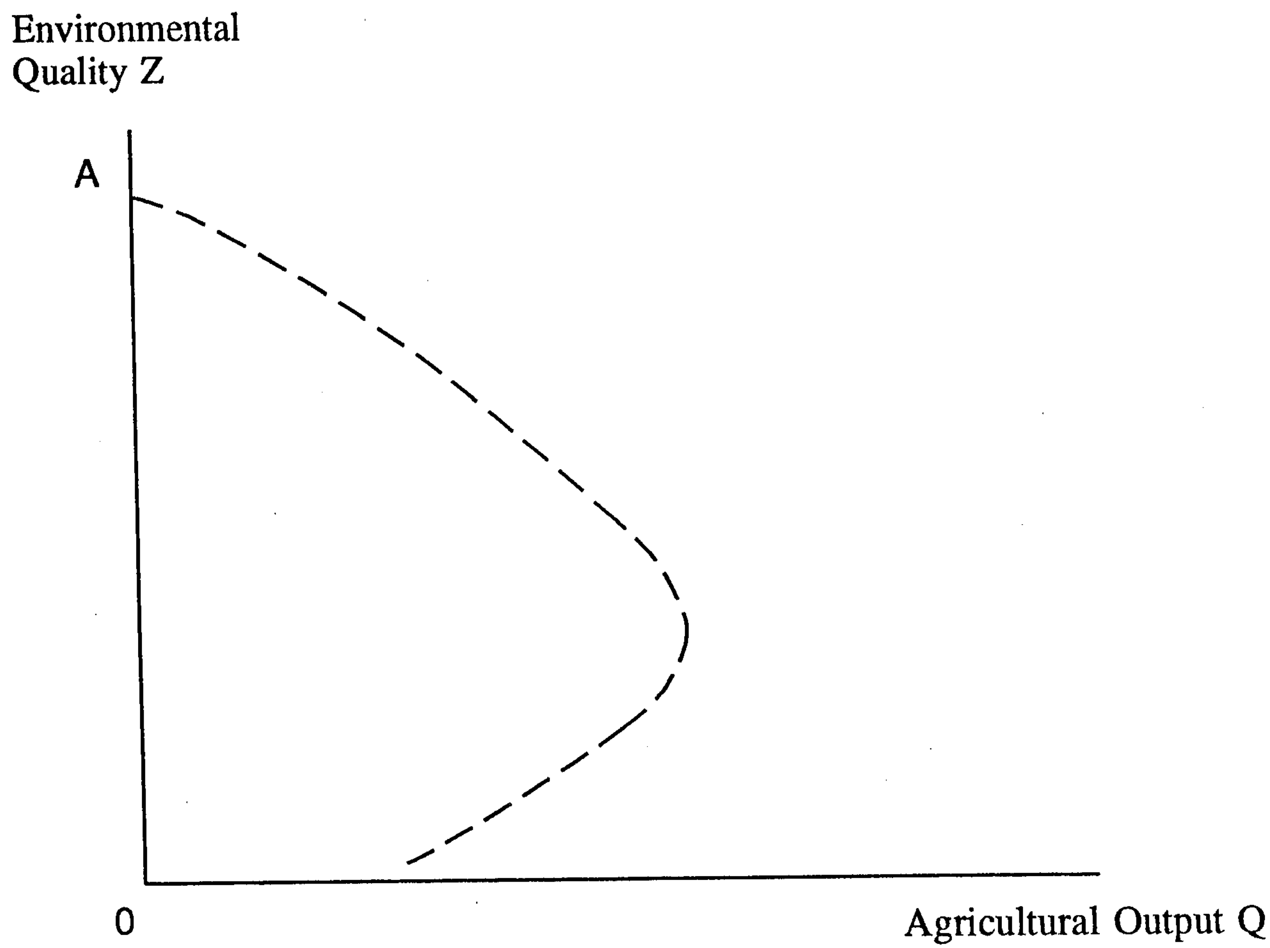


Figure 2. Transformation frontier for agricultural output and environmental services.

Figure 3. Potato Production Areas in Ecuador

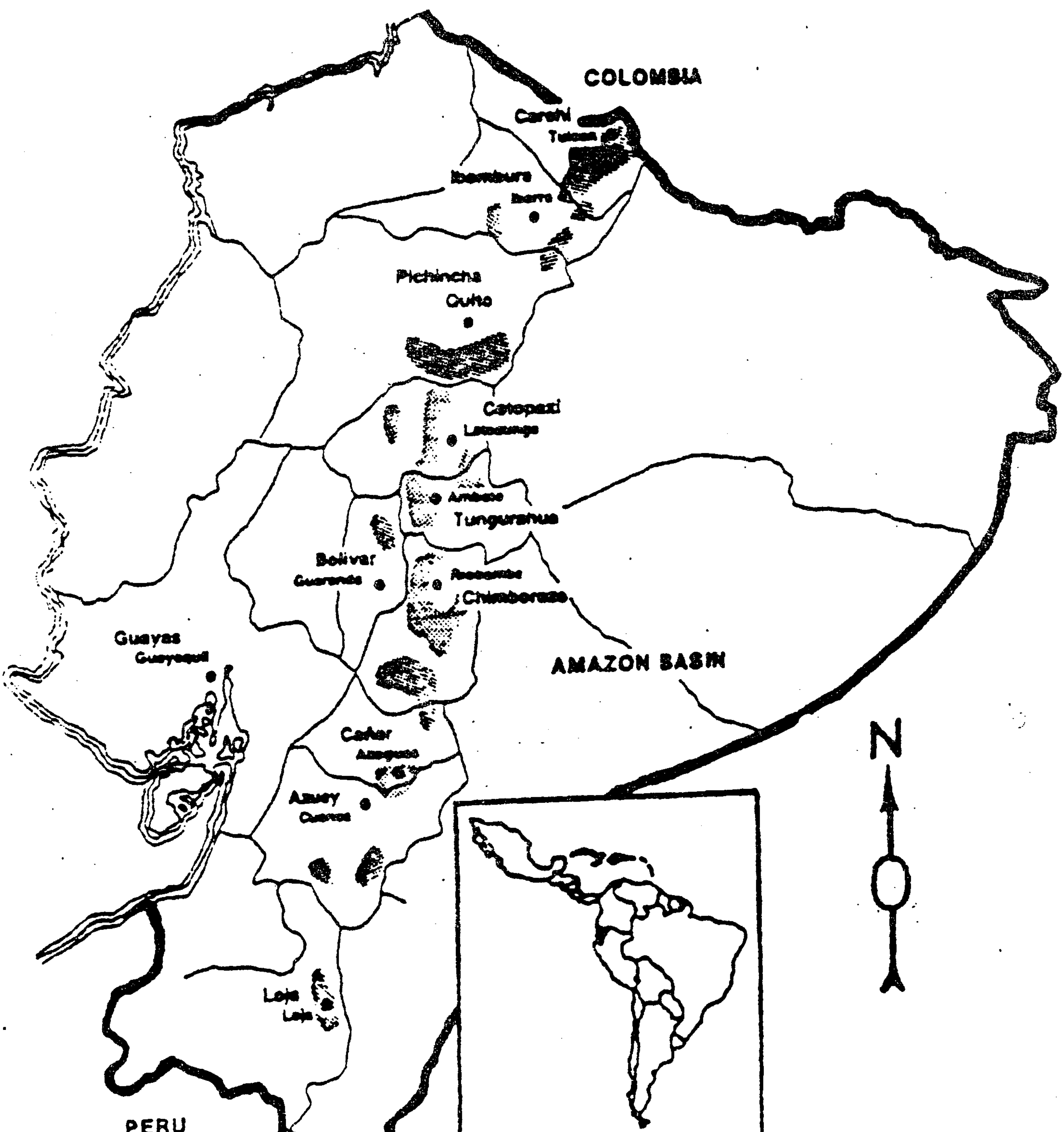
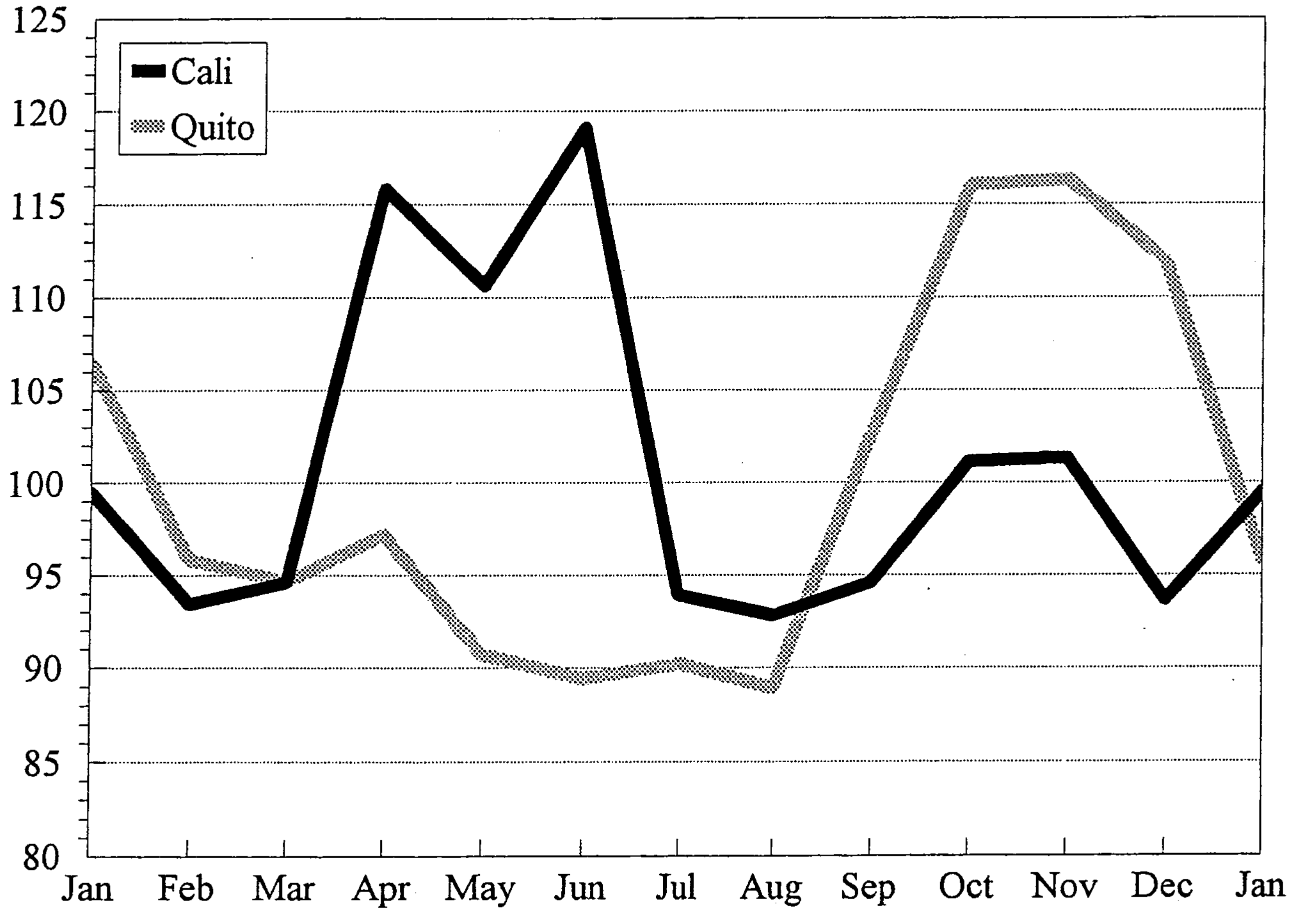


Figure 4
Index of Monthly Potato Prices
Cali and Quito



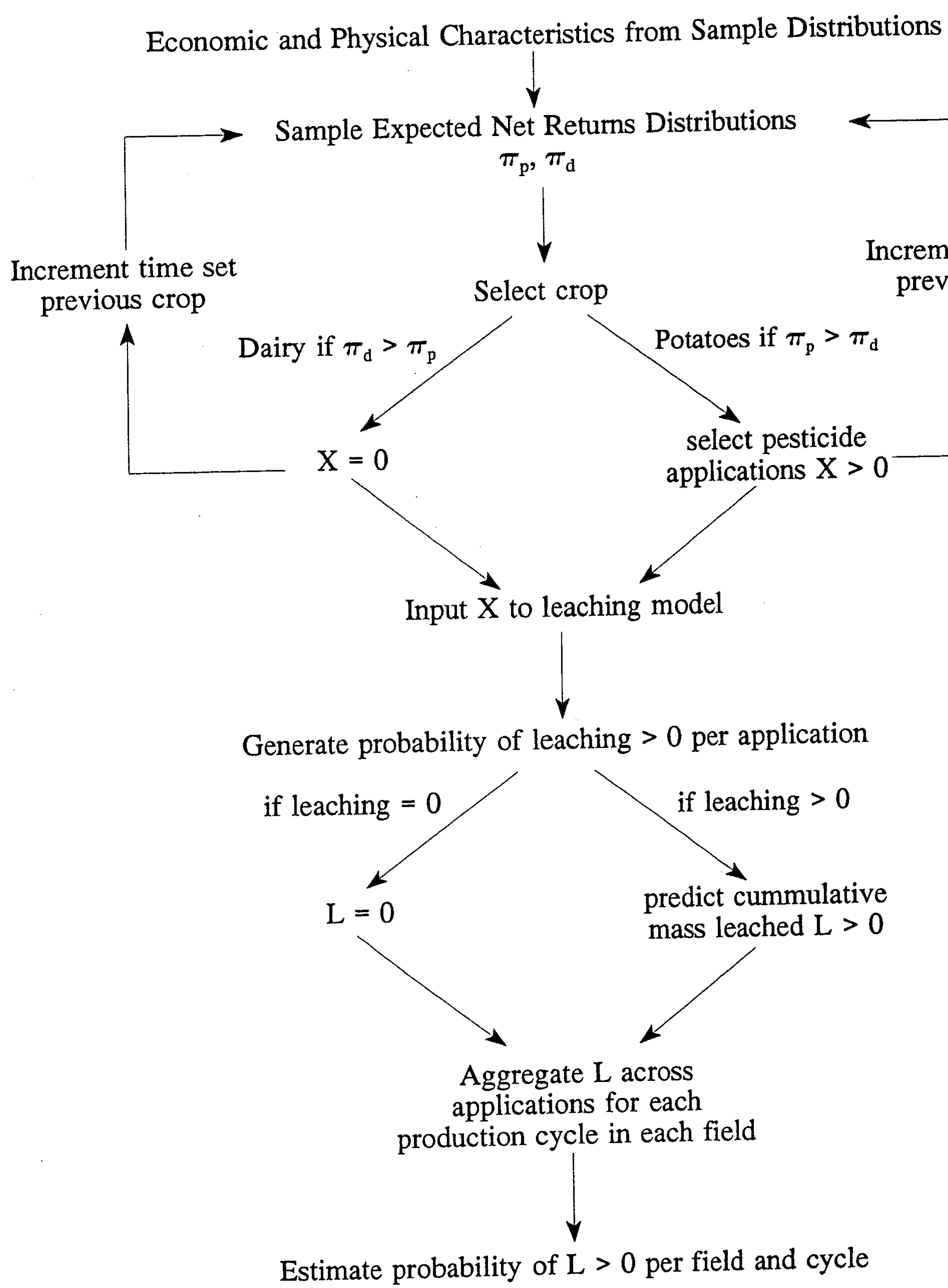
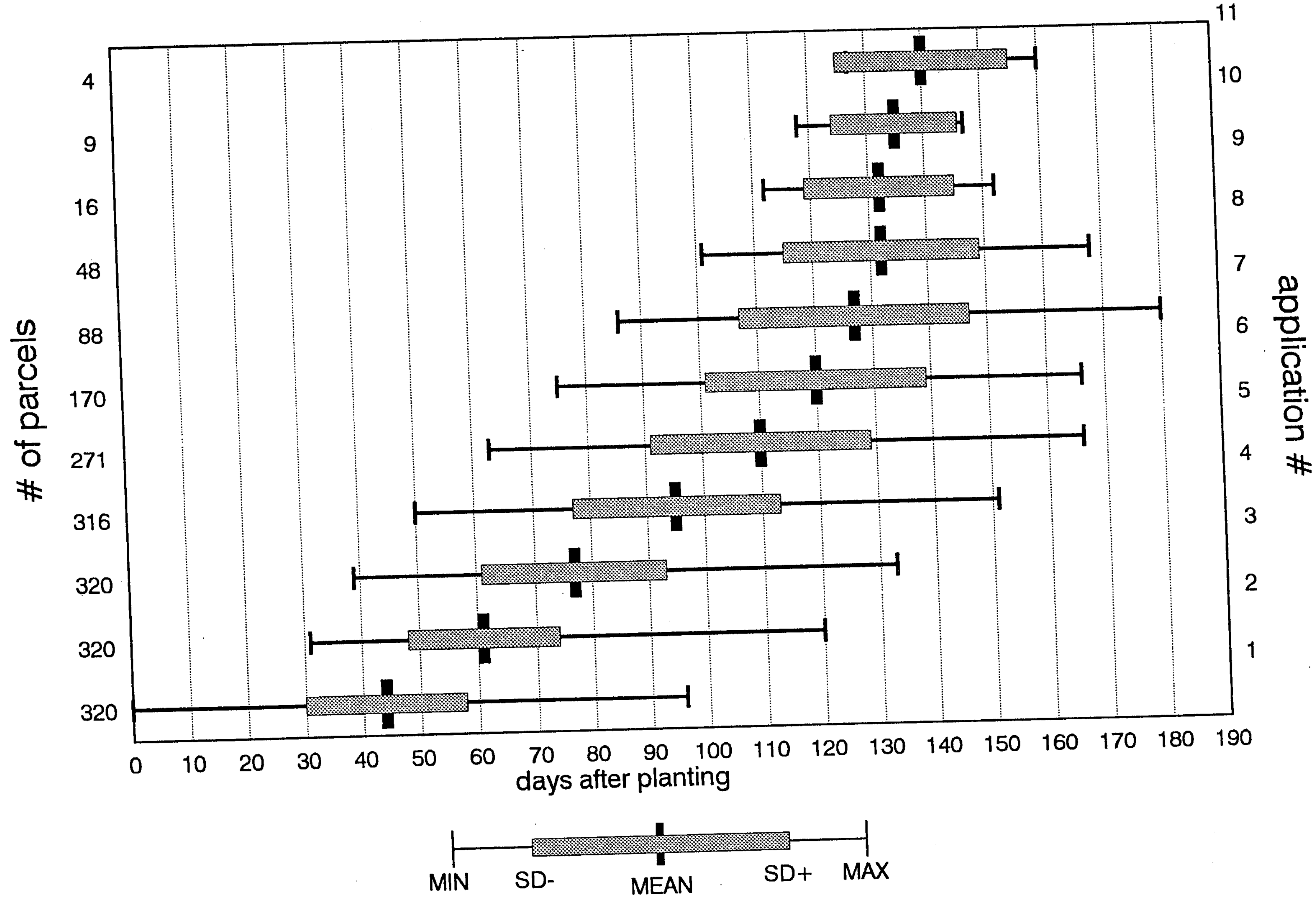


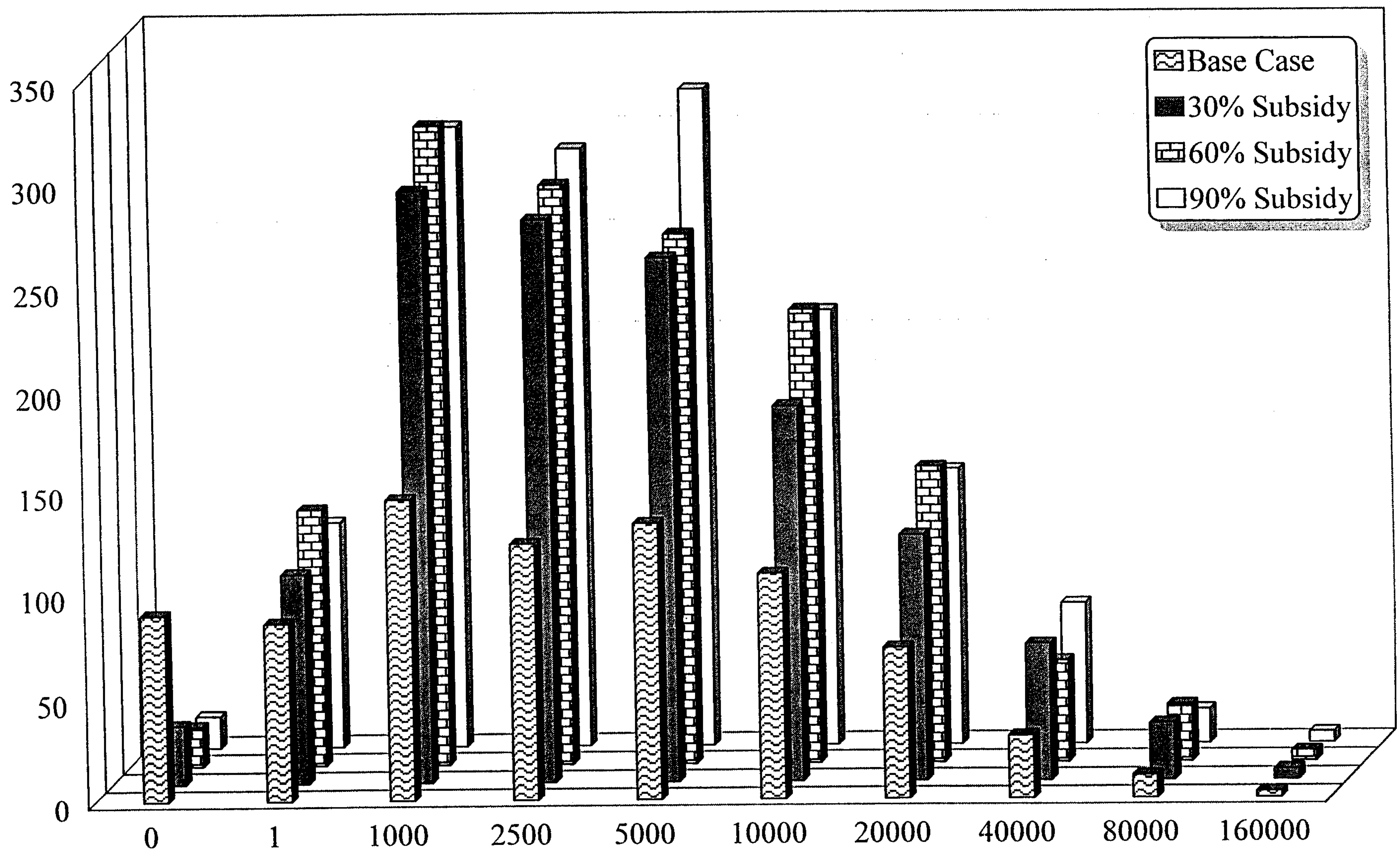
Figure 5. Integrated Economic/Physical Simulation Model

Figure 6. Timing of Fungicide Applications



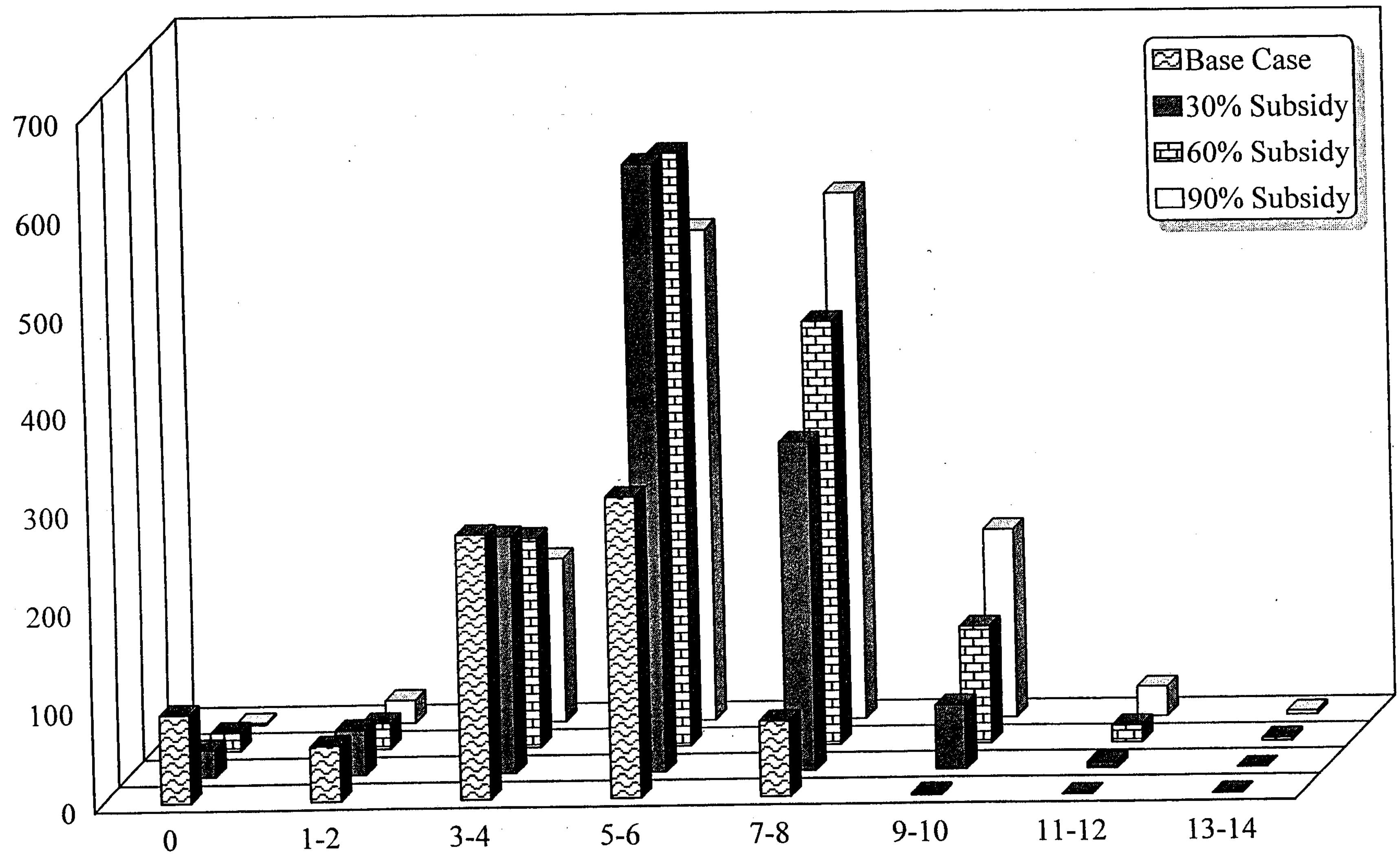
Source: Antle, Capalbo, and Crissman.

Figure 7. Fungicide Quantity Distributions for 30% Pesticide Tax and Potato Price Scenario



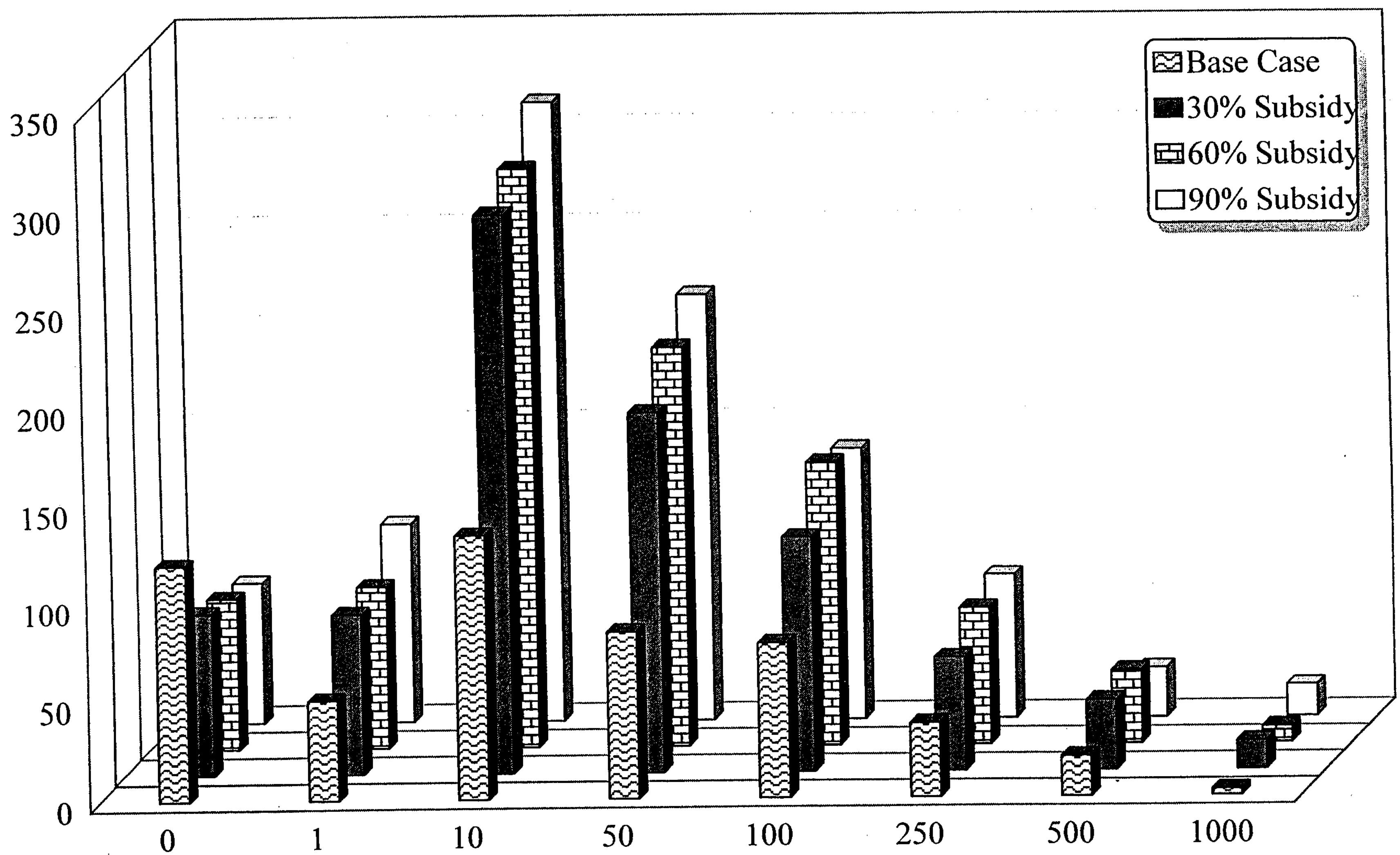
Note: Category 0 is multiplied by 10^{-1}.

Figure 8. Fungicide Application Number Distributions for 30% Pesticide Tax and Potato Price Scenario



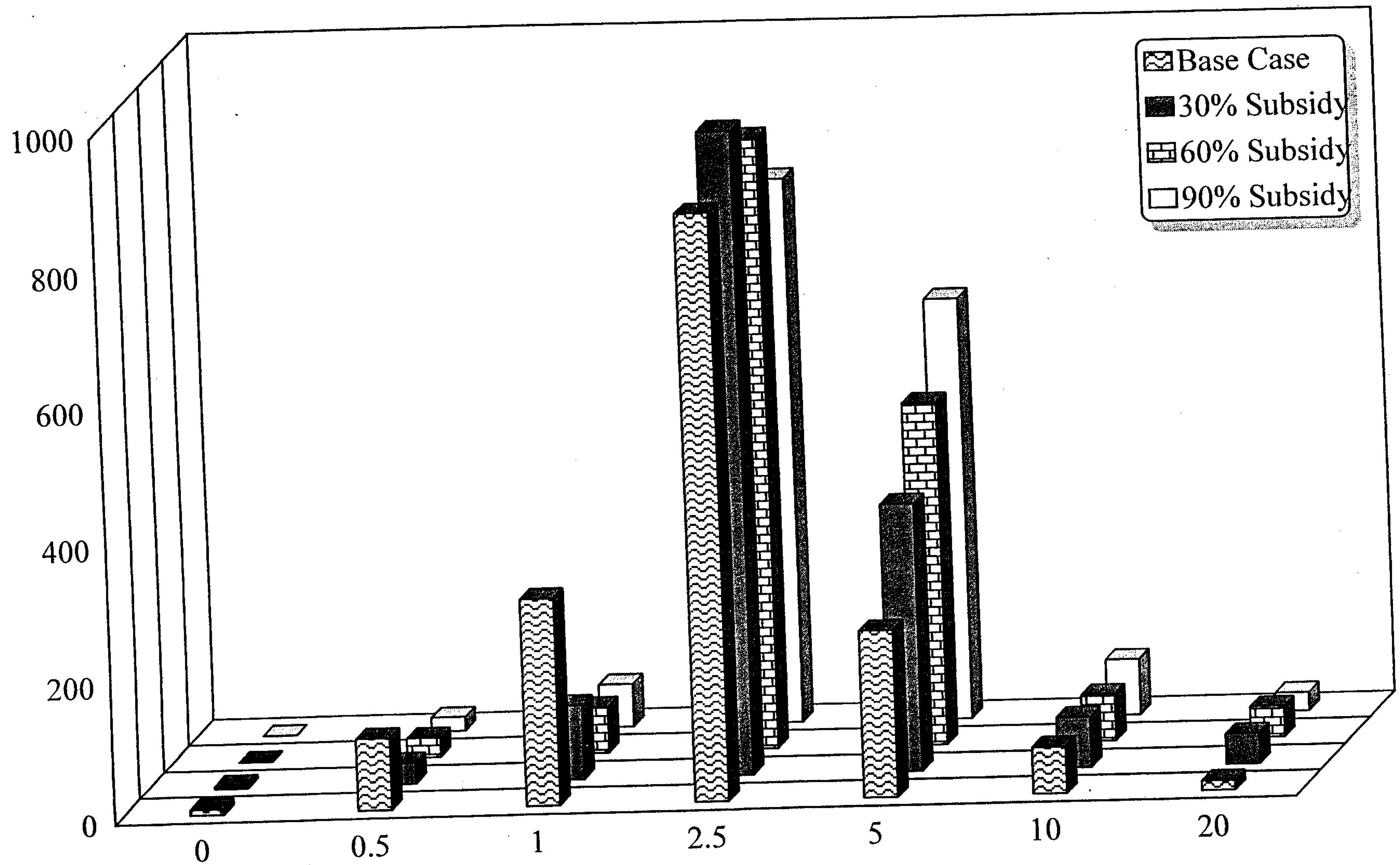
Note: Category 0 is multiplied by 10^{-1}.

Figure 9. Fungicide Leaching Distributions for 30% Pesticide Tax and Potato Price Scenario



Note: Category 0 is multiplied by 10^{-1}.

Figure 10. Revenue Distributions
for 30% Pesticide Tax and Potato Price Scenario



Note: Category 0 is multiplied by 10^{-1}.

Figure 11

Transformation Frontiers for Trade Liberalization Scenarios

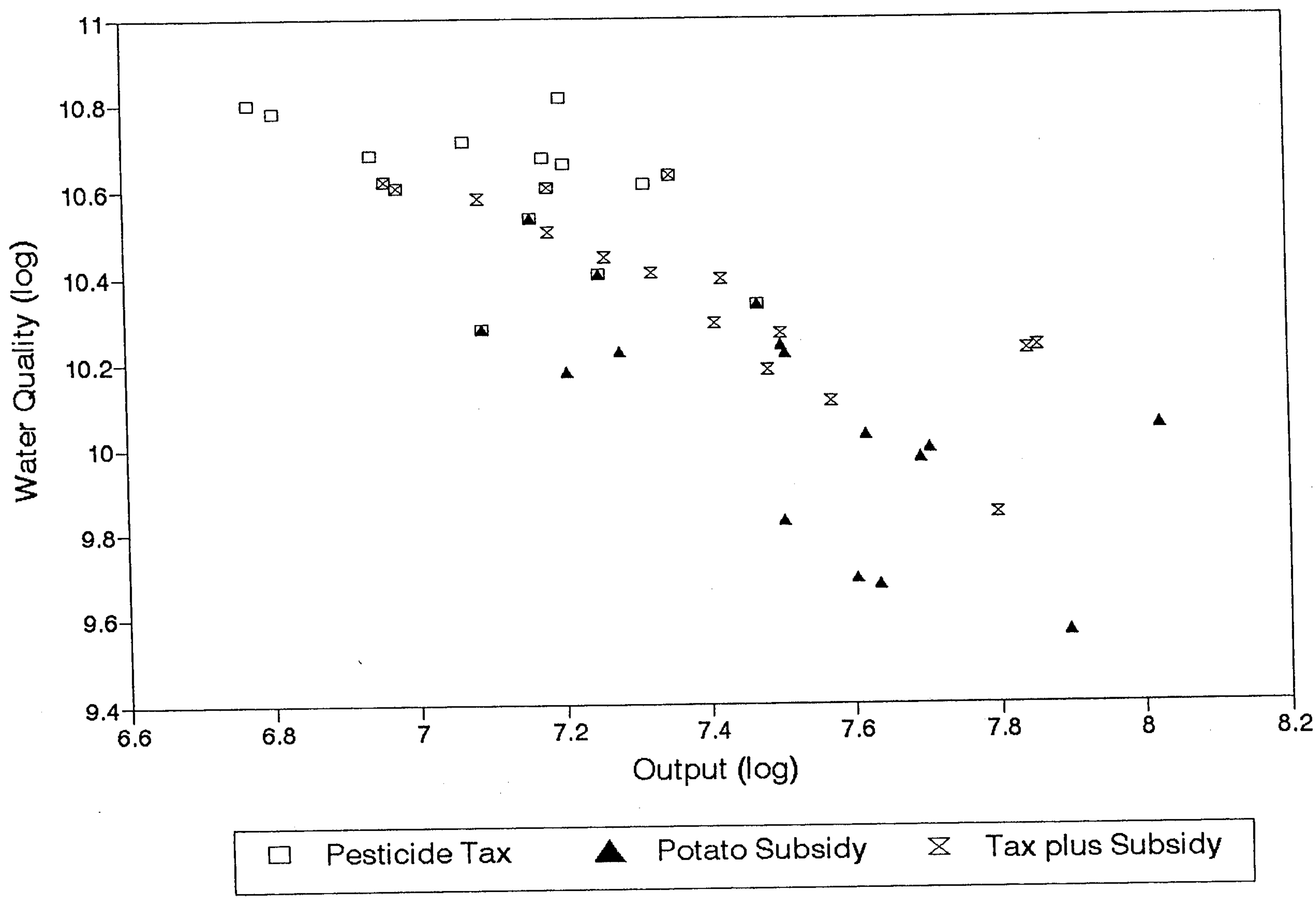


Figure 12

Transformation Frontiers for Trade Liberalization Scenarios