University Avenue Undergraduate Journal of Economics

Volume 7 | Issue 1 Article 1

2002

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I. Introduction

The last thirty years of agricultural history is the history of revolution. The first Green Revolution introduced sustained increases in cereal yields averaging 2.6% per year from 1950 to 1990, as vastly improved breeding techniques introduced drought resistance, pest resistance, increased complementarity of inputs, and increased the share of plant resources flowing to grain production. The second Green Revolution brought increasing awareness about the relationship of agriculture to long-term environmental sustainability and land degradation which was lacking in earlier decades. We stand now at the frontier of the third Green Revolution, as the possibilities of biotechnology and the continuing transformation of agriculture give rise to questions about the future of agriculture. Will supply continue to outstrip demand at such a pace that real grain prices will continue to fall, increasing the purchasing power of the poorer regions of the world? Will the poorer developing countries in Africa and Asia begin to close the gap between their own domestic supply and demand? What will be the environmental consequences of the drive to double grain production worldwide by 2050, and how will they affect our ability to reach that goal?

Though fifty years is a tremendous time horizon for the forecasting of any trend involving the complex interactions of billions of people and billions of hectares of intricate planetary ecosystems, the analytic methodology of economics is the most capable toolbox available for such forecasting. At the center of such a forecast are two complex functions, supply and demand, coevolving over time and codetermining prices, production, investment, labor flows, export patterns, and most other major variables. We begin in the first section of this paper with a discussion of the nature of evolving supply systems and demand systems in agriculture and the remainder of the economy. The second section of the paper introduces the structure and assumptions of the general equilibrium model itself. The third section presents the results of our baseline and alternative scenarios. The final section concludes the paper and discusses the implications of our projections.

II. Supply Side

In our analysis of the dynamics of the world economy over the next half century, we begin with the central issues in agricultural production, or the growth of 'the pile of grain.'

In a macroeconomic framework, the three major factors influencing the evolution supply of agricultural commodities in a particular region are technological improvements, investment and capital use, and labor supply flows, factors which interact with and co-determine international trade and environmental degradation. The role of government policies in our real-world agricultural economy is critical, though difficult to build into a macro model.

III. Technological Growth

Technological growth has made the greatest contribution to the increase in yields historically, and is expected to do so into the future. World cereal production increased by 185 percent between 1950 and 1990, with 90 percent of this increase due to higher yields, and only 10 per cent due to increased land area (Mitchell, 1997). Even as traditional breeding techniques reach what may be their limits, the contribution of biotechnology to agriculture should ensure that technology will continue to play a key role in growth of production. Technological growth is not only central to the growth of agricultural production, but to overall GDP growth across time and regions; Robert Solow described this phenomenon in the United States, finding that over 85% of GDP growth over time could not be explained by increases in capital and labor.[1]

[1] Robert Solow (1957)

Generally speaking, technological growth does not fall like “manna from heaven”, but is directly correlated with specific investment in research and development. Hence, changes in the level of investment in research would significantly impact the expected rate of technological growth and increases in agricultural yield. The link between research investment and technological growth has created regional differentials in agricultural yield and technological growth in general. Because research tends to exhibit diminishing returns in yield growth, developed countries' agricultural yields are already closer to the physical limits of nature than are the yields of developing countries. However, the World Bank study of biotechnology's potential to increase agricultural productivity indicated that notable progress could be expected. (Mitchell, 1997) Developing countries also have significant opportunities to adapt technologies already developed in the OECD for use locally; these opportunities are tempered by climatic differences and differences in the appropriateness of varying production technologies.

In modeling technological growth, it would be most appropriate to develop a framework in which investments in technology were determined endogenously through relative costs and returns of investment in research. This was one of the original missions of the modeling team, but the experimental specifications of endogenous technology growth generated more dynamic instability than the modeling team had time to dampen. Though exogenous specifications of technology growth are theoretically weak, empirically they can at least approximate trends in total factor productivity growth, and thus represent the final approach in this specification of the model.

IV. Capital

Though historically less important than technology growth, capital used in agricultural production influences the supply of cereals. Agricultural capital traditionally includes equipment and inputs such as tractors, oxen, fertilizer, seed, and means of obtaining water such as wells and irrigation systems. Inputs such as seed and fertilizer can be regarded as capital inputs which depreciate in one period.

In the agricultural sector, land constraints imply decreasing returns to scale, and thus capital and labor elasticities of yield sum to less than one; one cannot simply pile tractors on top of one another in South Asia and achieve productivity increases. Production in the non-agricultural sector is characterized by Cobb-Douglas constant-returns production functions.

Investment in each year offsets the depreciation of capital, and, if great enough, brings net increase in capital stock. Income that is saved can be invested to increase capital stock, and thus incomes and savings levels in economies determine the gross resources available for investment.

V. Labor

Labor is the backbone of any system of production, agricultural or otherwise. Despite this, changes in labor supply generally do not account for a large share of increases in production. Developing countries generally are characterized by a high share of labor in agriculture, over 50% in poorer regions and even higher in selected Asian and African countries.[2] As this labor is generally not augmented by high levels of technology and physical or human capital, such labor tends to be relatively unproductive. Arthur Lewis noted this long ago in India, and his ideas, as well as many of his contemporaries', were centered on methods of removing labor from the unproductive agricultural sector. Developed countries, on the other hand, tend to have less than ten percent of their labor force in agriculture.

[2] World Bank, 2001

Labor can be modeled as a partially mobile factor of production which flows between the agricultural and non-agricultural sectors based on relative labor productivity differentials in these different sectors, using relative productivity as a proxy for relative wage differentials. The development process of structural transformation tends to fuel growth of non-agricultural industries, drawing labor resources out of the agricultural sector and increasingly urbanizing the region in question. On the other hand, major slumps in nonagricultural production can lead to more labor flows back into to agriculture. According to Conway, over 3.5 billion people will be urban dwellers in 2020, and most will be food consumers rather than producers (Conway, 1997) It is interesting to note that populations tend to settle primarily in fertile areas, causing an inherent competition between urban-industrial development and agricultural production; this is beyond the scope of our model, but substantial population increases may lead to decreasing availability of cropland in the future.[3]

VI. Land

Land is obviously a major input in production of agriculture. However, over the past few decades there has been little change in the amount of land area under cultivation; as we saw previously, less than ten percent of production growth in agriculture has been due to increasing cropland. The land base may even slightly decline over the near future because less productive land already under cultivation may not be profitable to farm. Under assumptions of constant land use over time, land area in a dynamic production model acts more as a constraint than a variable.

[3] see Mitchell, 1997

VII. International Trade

In addition to regional production, *domestic* supply of both agricultural and nonagricultural products can be generated through international trade. In monetary terms, cereals are now only second to petroleum in international trade.[4] Different regions have comparative advantages in the production of certain types of goods based on relative factor prices; labor-intensive production goods are most likely to be imported by developed countries and exported by developing countries, while capital-intensive production goods exhibit the opposite trade patterns. The share of world exports going to the developing countries has grown from 13 per cent in the early 1970s to more than 26 per cent in the 1990s. High world prices for food, while decreasing the real income of consumers, increase the returns to food production and thus stimulate agricultural development in underdeveloped regions. The simplest and most widely used model of international trade describes a single world price for a given commodity or set of commodities which stimulates differential levels of supply and demand.

Governmental policy can influence agricultural output positively or negatively. Policies such as taxes or subsidies distort the relative returns to the agricultural and non-agricultural sectors; trade barriers alter the relationship between real factor costs and product prices. Developing countries in Africa and Latin America historically were characterized by major policy biases towards the urban sector and by heavy trade barriers, distortions brought about both by the political economy of political power and tenure maximization and partially by the influence of the work of early growth economists such as Lewis and Harrod. The modeling of the world-level macroeconomic effects of government policy is a fascinating area of research but is beyond the scope of this model.

[4] Conway, 1997

VIII. Sustainability

In the long term, agricultural sustainability is necessary to maintain yields and agricultural output. Environmental issues such as soil degradation, water depletion, and the effects of global climate change all work to reduce agricultural output for a given set of inputs over time. One set of regional estimates put forth by the Global Land Assessment and Degradation Agricultural exercise estimates total global degradation since the Second World War at 2 billion hectares, or 22.5 per cent of the world's agricultural, pasture, forest, and woodland (Conway, 1997). Agricultural research and development can counteract some of these environmental concerns by creating more environment-conscious techniques into the agricultural production. During the development of the wheat programme in the Green Revolution, experiments showed that newly fertilized, properly irrigated soils containing 140 kg/ha of nitrogen raised yields more than fourfold. Even on rain-fed soils, yields more than doubled and the addition of phosphates in the form of fertilizers produced five- or sixfold increases (Conway, 1997). Appropriate use of fertilizer is also a major issue, as many ecosystems suffer from heavy runoffs of nutrients generated by the overuse of fertilizer. In general, the entire supply side of the world food economy is heavily constrained by issues of sustainability; the importance of introducing and spreading sustainable production techniques cannot be overemphasized.

IX. Demand

The simplest way to think about the growth of aggregate demand for grain consumption over time is in terms of three variables:

Demand for food = f (population, per capita income, relative prices)

These three factors are central in the determination of demand and demand growth over time; they are also highly interrelated. A macro-level analysis / forecast of the demand for grain in the world food economy should be focused on the movements in, and the relationships between, these three variables; specifications which include such data as urbanization and trade levels explain little additional variation. Boserup provides an interesting case for the role of population growth in influencing long-term grain production trends, but empirically such a relationship is very shaky.[5]

X. Population Growth

Population growth is the driving force of growth in the demand for agricultural products. If one were to describe the 'population elasticity of demand', the percentage change in demand generated by a one percent change in population, it would be unity; unlike all other factors in a theoretical demand equation, population is a direct scalar. Any sort of quantitative analysis and forecast of the world food economy will be highly sensitive to assumptions regarding population growth rates and the decline of those growth rates.

There is a general consensus that over time the world population growth rate will decline, with population growth rate slowing fastest in developing regions (Mitchell et al, 1997). Dynamically increasing levels of per capita income, education, and contraceptive use in developing countries account for the majority of this slowdown in growth rates; developed countries in general are close to the population replacement rate. The regions with the highest population growth rates, such as the Middle East, Africa and South Asia, are expected to experience the largest decline in population growth rates. Africa is projected to experience considerable population growth slowdown not only due to rising income and education, but due to the spreading AIDS epidemic, a notably less benign form of population control.

[5] see Boserup, 1975

Despite the considerable decline in growth rates of population across developing countries, population levels will rise significantly over the next fifty years, driving up the demand for agricultural products by no small amount (Mitchell, 1997). The World Bank forecasts that the world will contain over 8 billion people by 2020 alone; more than 80% of the increase is expected to come from the growth of Asian and African populations.[6] In the past, population growth has accounted for between one-half and two-thirds of the increased consumption of cereals, a trend that is expected to continue into the future.[7] In dynamic modeling of the world food economy, it is possible to model population growth endogenously, though very few scholars have attempted such a deed. It is perhaps more reasonable in macro modeling to describe population growth exogenously, utilizing the predictions of institutions such as the World Bank, though perhaps structured differently. This is the approach utilized in our model.

XI. Income Growth

While, as we have argued, it is tightly interrelated with population growth, the growth of per capita income has a separate and large impact on the demand for agricultural products. All but the most pessimistic projections acknowledge that most regions will experience at least some degree of per capita income growth in the next fifty years.

As per capita incomes increase, particularly in developing countries, the increased purchasing power of the majority of the population will drive up demand for agricultural products. Demand is most sensitive to income growth in the poorest regions of the world, sub-Saharan Africa and South Asia, as vast numbers of people within those economies spend the majority of their meager income on low-quality grains; many are chronically undernourished.

[6] World Bank, 2001

The income elasticity of demand for direct grain consumption, so to speak, drops rapidly as income rises, congruent with Engel's law; as income increases, families spend a smaller share of their household budget on food. Thus, developed countries generally exhibit a very low, even negative, income elasticity of demand for *direct* grain consumption, as they spend the greatest share of their income on nonfood and higher-quality food commodities.[8]

However, if we analyze the elasticity of demand for *indirect* grain consumption, the story changes somewhat. Bennet's Law states that as income increases, the share of caloric intake in starchy staples decreases; over the development path we observe shifts away from the consumption of grains and towards the consumption of meat and other luxury agricultural commodities. Japan's per capita rice consumption declined from 107 kilograms to less than 65 over the past four decades, while its meat consumption increased from approximately 5 to 40 kilograms (Mitchell, 1997). Eight kilograms of grain are needed for every kilogram of beef consumed; five kilograms are needed for every kilogram of pork, and two are needed for every kilogram of poultry. Thus, the demand for indirect grain consumption increases even if direct consumption levels off or fall; income elasticities of demand for the *indirect* consumption of grain remain positive, and higher in all cases than income elasticities of demand for direct consumption.

An interesting aspect to consider is that while Bennet's Law holds true generally, cultural factors, particularly religion, can at least partially deflect the trend towards meat consumption. Religious beliefs in highly vegetarian India, for example, have staved off significant growth in meat consumption in comparison to other countries.

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[7] World Bank, 2001

[8] for a discussion of this issue, see Cranfield, John A.L.; Hertel, Thomas W.; Eales, James S.; Preckel, Paul V., Dec, 1998

In modeling food demand dynamically as a function of income growth, it is possible to utilize the predictions of various institutions; income growth can easily be modeled as an exogenous variable. Though more theoretically involved and difficult, it is also possible to model income growth endogenously, as a function of technological advance, capital accumulation, and labor flows, as does our model.

XII. Real Prices

Prices, of course, have significant equilibrating effects on demand. As for any good, the price elasticities of demand for agricultural commodities are negative. Lower real food prices cause substitution in consumption expenditures toward agricultural commodities, in addition to increases in the real income of consumers. The trend of decreasing world food prices has undoubtedly played an important role in driving grain consumption up over the last forty years.

It is vital to recognize the relationship between price elasticities of demand for grain and per capita income. The price elasticity of demand for grain tends to be relatively inelastic, given the necessity of food consumption and the stickiness of diet preferences. However, this does not necessarily hold in poor developing countries, in which very low income individuals find their real incomes drastically reduced by grain price increases. This intuition is contained in Timmer's Law, which states that shifts in food prices cause the poor to suffer the greatest decreases in food consumption, as they spend a greater share of their total budget on food. When food prices increase in developed countries, most people can substitute cheaper foods into their diets rather than reducing the quantity of food consumed. In contrast, poor people in developing countries suffer decreasing quantities of food consumption as prices increase, as they already consume primarily inferior goods and have few opportunities for substitution.

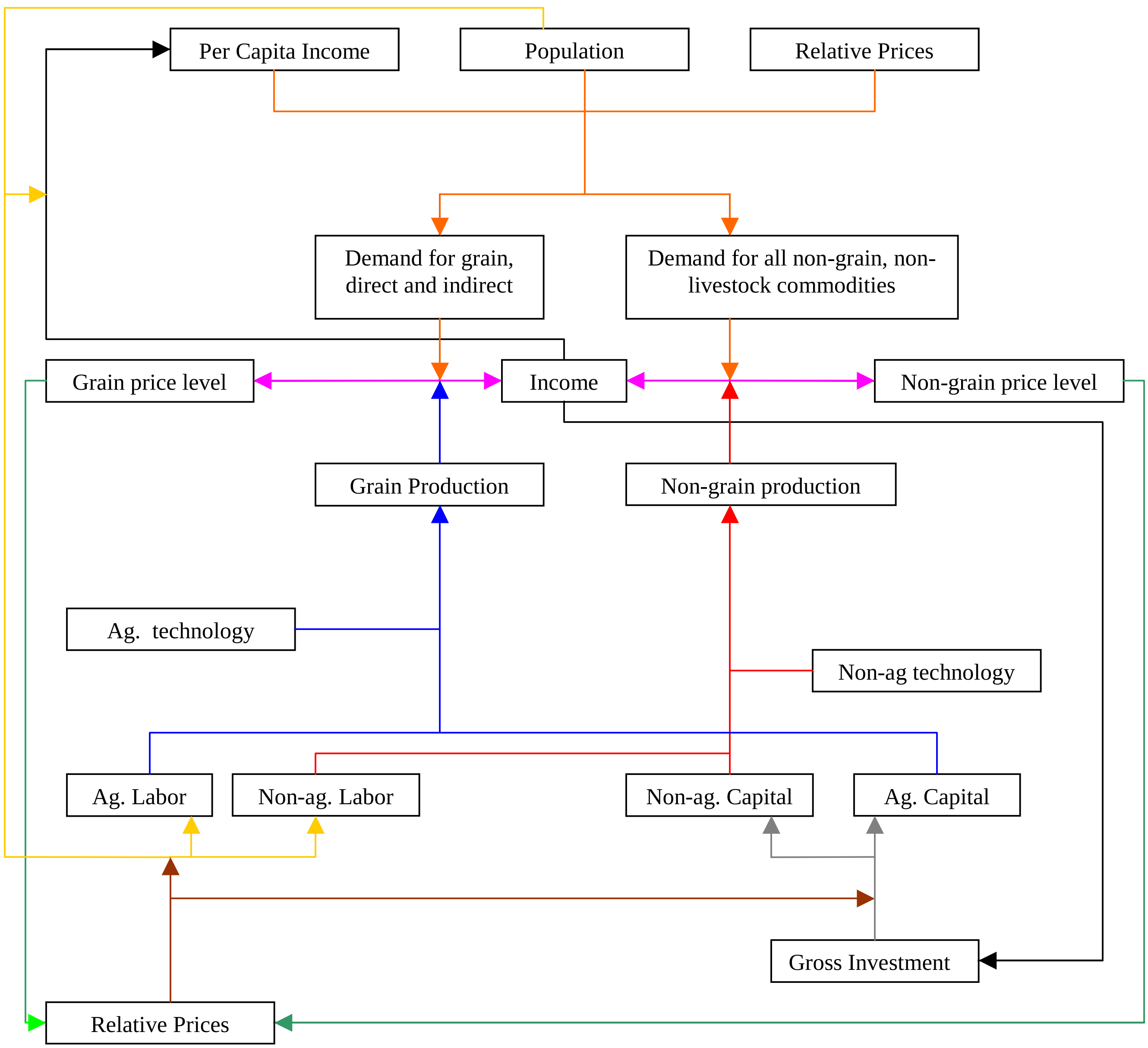
In modeling price shifts dynamically, prices must act as the equilibrating factor between worldwide supply and demand, imports and exports. It is also critical to allow price elasticities of demand to vary with income growth, a relationship integrated into the model.

XIII. A Few Remarks

The relevant question is, of course, will future trends in the worldwide supply of and demand for grain drive prices further down, or will prices rise over time, decreasing grain consumption the most in the world's poorest regions? This question is very sensitive to initial assumptions about population growth, technological progress, environmental degradation, among other things; for this reason it is desirable to run a number of alternate scenarios on varying assumptions regarding the model's exogenous variables. We hope that the reader will find what follows to be as interesting as we found the process of developing it.

XIV. Structure of the Model

The following pages describe the general structure of the model. Every variable but price is set not only in time but across nine regions.[9] The below diagram represents a structural overview of the major dynamic flows of the model.



[9] A list of regions modeled and countries included in each region is included in appendix A.

XV. Two-Sector Definition

The forecasting model is defined through a two-sector general equilibrium approach, separating the grain-producing sector (often referred to as, though not completely equivalent to, the agricultural sector) and an aggregate sector which comprises all other production (often referred to as the 'non-agricultural' sector).[10] Commodities produced in the grain-producing sector are demanded both for human consumption, livestock consumption, and numerous other minor uses, and thus we can refer to the demand for such commodities as the demand for *indirect* grain consumption. As such, the following identities hold:[11]

[1] $Y_{i,t} = Y_{a,i,t} + Y_{na,i,t}$

[2] $I_{i,t} = I_{a,i,t} + I_{na,i,t}$

[3] $L_{i,t} = L_{a,i,t} + L_{na,i,t}$

XVI. Production Functions

The model specifies separate Cobb-Douglas production functions for the agricultural (grain-producing) and non-agricultural sectors; international trade is specified through a traditional excess supply / excess demand schedule. The agricultural production function [4] is simply specified as yield multiplied by cropland, defining yield [5] as a function of agricultural productivity, capital per hectare and labor per hectare, and exhibits decreasing returns to scale, thus building land constraints into the model. The nonagricultural production function exhibits constant returns to scale and is a conventional neutral technology Cobb-Douglas specification.

[4] $Y_{a,i,t} = C_i * ye_{i,t} + NX_{a,i,t}$

[10] similar two-sector ag. / non-ag. specifications are found as early as Tolley and Smidt (1964)
[11] Variable and parameter definitions can be found in appendix B.

[5] $ye_{i,t} = A_{a,i,t}(K_{a,i,t} / C_i)^{ά1}(L_{a,i,t} / C_i)^{ά2}$

[6] $Y_{na,i,t} = A_{na,i,t}(K_{na,i,t})^{ά3}(L_{na,i,t})^{ά4} + NX_{na,i,t}$

XVII. Investment and Capital Accumulation

Gross investment is specified endogenously as equal to gross domestic savings [7]. Investment flows into the two sectors through [8]. The ratio of the partial derivatives of the production functions with respect to capital proxies for expected relative returns to investment in the two sectors. Gross investment flows into the two discrete sectors according to a function of the expected relative returns to investment in the two sectors.[12]

Capital accumulation equations [9] and [10] are traditional difference equations relating depreciation, gross investment, and dynamic changes in the capital stock.[13]

[7] $I_{i,t} = s_{i,t}Y_{i,t}$

[8] $I_{a,i,t} / I_{na,i,t} = [(P_{a,t-1})(\delta Y_{a,i,t-1}/\delta K_{a,i,t-1}) / (P_{na,t-1})(\delta Y_{na,i,t-1}/\delta K_{a,i,t-1})]^{\rho 1}$

[9] $K_{a,i,t} = (K_{a,i,t-1})(1-\delta_{ka}) + I_{a,i,t}$

[10] $K_{na,i,t} = (K_{na,i,t-1})(1-\delta_{kna}) + I_{na,i,t}$

XVIII. Population Growth and Labor Force

Population growth is specified exogenously using traditional difference equations, tracking both population growth rates and the slowdown of those growth rates:

[11] $N_{i,t} = (N_{i,t-1})(1+g_{i,t})$

[12] Though econometric analysis can be used to determine the appropriate value of the investment response to expected relative returns in this framework, the modeling team is not completely satisfied with this specification of investment, and a more theoretically rigorous specification is currently in the process of being tested.

[13] such difference equations are very common, possibly most famously used in Solow's original growth model

[12] $g_{i,t} = (g_{i,t-1})(1-\delta_{gp})$

The total labor force available in a given region is given by a certain share of its population [13], and is the sum of the labor force in the agricultural and nonagricultural sectors. Labor flows are modeled through a somewhat similar mechanism as investment flows. It is assumed that the ratio of employment in the agricultural sector to employment in the nonagricultural sector depends on the lagged ratio of sectoral employment and on changes in the relative wage offers in the two sectors. The ratio of the partial derivatives of the sectoral production functions provide a proxy for relative productivities of labor, and thus relative wage offers.[14]

[13] $L_{i,t} = \varepsilon N_{i,t}$

[14] $(L_{a,i,t}) / (L_{na,i,t}) = (1-\psi)[(L_{a,i,t-1})/(L_{na,i,t-1})] + \psi(w_{a,i,t-1}/w_{na,i,t-1})^{\rho 2}$

[15] $w_{a,i,t-1} / w_{na,i,t-1} = [(P_{a,t-1})(\delta Y_{a,i,t-1}/\delta L_{a,i,t-1})] / [(P_{na,t-1})(\delta Y_{na,i,t-1}/\delta L_{a,i,t-1})]$

XVIV. Technological Growth

The modeling team originally set out to model technology growth endogenously through a similar mechanism as used in investment flows; the idea was to allow investment to be allocated not only to physical capital but also to research and development, and through the introduction of some ‘cost of technical advance’, allow market forces to determine technological progress in this way. Unfortunately this specification induced a degree of instability into the model that we did not have time to correct. Though exogenous specifications of technology

[14] For theoretically similar specifications in non-forecasting models, see for example Casas (1984)

growth are theoretically weak, empirically they can at least approximate trends in total factor productivity growth, and thus represent the final approach in this specification of the model in the form of twin difference equations [18] and [19]. It is worth noting that we assume decreasing rates of technical advance in this specification.

[18] $A_{i,t} = (A_{i,t-1})(1 + g_{a,i,t})$

[19} $g_{a,i,t} = (g_{a,i,t-1})(1-\delta_{ga})$

XX. Demand

Demand is specified for both agricultural and nonagricultural commodities. The demand for agricultural commodities is in truth the demand for indirect grain consumption, and thus the overall demand for grain; the explicit modeling of livestock and alternative dietary commodities is beyond the scope of this model, but indirect grain consumption does take into account all sources of demand for grain.

The demand equations themselves, [20] and [21], are functions of population levels, per capita income levels, and price levels.[15] Price and income elasticities are specified through polynomial approximations as functions of per capita income, capturing the important fact that such elasticities are not constant across time and region, but depend primarily on income levels.[16]

[20] $D_{a,i,t} = N_{i,t}(Y_{i,t} / N_{i,t})^{\mu 1}(P_{a,t})^{\lambda 1}$

[21] $D_{na,i,t} = N_{i,t}(Y_{i,t} / N_{i,t})^{\mu 2}(P_{na,t})^{\lambda 2}$

[15] Similar demand specifications in general equilibrium models include Rosegrant (1995, 2001), Mitchell (1997)
[16] Appendix D discusses these polynomial approximations.

XXI. International Trade Equilibrium

The equilibrium in international trade provides the solution to the set of equations specified over the forecast period. The General Algebraic Modeling System (GAMS) language uses a Gauss-Seidel iterative procedure to minimize the sum of net exports, satisfying the logical conditions [22] and [23] such that imports equal exports.

[22] $\Sigma_t NX_a = 0$

[23] $\Sigma_t NX_{na} = 0$

XXII. Baseline and Alternative Assumptions

Because general equilibrium models of this character are generally quite sensitive to initial assumptions regarding critical exogenous variables (in this case including population growth, TFP growth and environmental degradation), it is advisable to run a number of scenarios which alter baseline assumptions in various theoretically informed and interesting ways. For the purposes of this paper, we ran one baseline case and six alternative scenarios. We describe the seven cases and briefly summarize their results; for a much more complete set of relevant graphs and data, see Appendix C.

1. Baseline Case

The baseline case was run under fairly conventional assumptions. Population growth rates were specified as slowing by between one and two percent per year (not to be confused with *percentage points*), more rapidly for developing countries than developed countries. TFP growth rates were specified similarly as between .5% and 1.5% initially and declining by close to one percent per year. No environmental degradation parameter was introduced into this specification.

The remainder of the model was calibrated to closely approximate current production and demand levels and allowed to run to 2050.

The baseline assumptions yield relatively optimistic results; worldwide grain production increases to approximately 3.9 billion tons by 2050, driven in great part by yield growth in North America and East Asia. The world population level is projected to be approximately 10.2 billion, an increase of approximately 70% over current levels. Supply systematically outpaces demand, driving real food prices down 40% over the next fifty years.

At this point it is worth pointing out an interesting peculiarity in the estimates. As a result of the model's assumptions of open world markets, less competitive agricultural sectors held up by subsidies and trade barriers tend to shrink rapidly between 2000 and 2010 as the sectors dynamically equilibrate. This yields shrinking grain production in Europe and rapid acceleration of imports in South Asia, among other results. In general, trends in the early forecast years contain biases arising from similar disequilibrium effects, a fact which should be taken into account when analyzing these predictions.

2. Rapid Slowdown of Yield Growth

Many argue that there is a significant change that agricultural yields, especially in developed countries, are nearing some biological ceiling level. The expected results of a scenario modeling this prediction (by increasing the rate at which agricultural yield growth slows by a factor of four) include slowing grain production and smaller drops in real grain prices over time, or even price increases. Indeed, this specification projects grain production in 2050 of closer to 3.4 billion tons; this drop is estimated to be significant enough to drive real grain prices up approximately 12% over the period of the forecast.

3. High Technology Growth

An alternate and more optimistic scenario models general TFP growth rates which are 20-30% higher than in the baseline scenario. This scenario yields even more optimistic price predictions than the baseline; real grain prices decrease by 48% from 2000 to 2010, as grain production reaches approximately 4 billion tons per year.

4. Low Population Growth

As we expect the model to be sensitive to changes in population growth rates, it is critical to run scenarios with different assumptions about the slowing of population growth rates. This first, low-growth scenario yields population level predictions of ~8.65 billion, allowing supply to even further outstrip demand; real grain prices fall by approximately 47% from 2000-2010.

5. High Population Growth

We expected the high population growth scenario to yield increasing real grain prices over time. However, the model predicted that, given the original assumptions about technology and the lack of environmental degradation, even a projected population level of 12.6 billion is not enough to keep real prices at their 2000 levels. Real prices are estimated to fall by approximately 24% even in this case.

6. Mild Environmental Degradation

In this case, the modeling team introduced a dynamic environmental degradation parameter into the agricultural production equations, designed to increasingly affect agricultural production and reaching its maximum damage level of 10% of production by 2050. The effect is predictably small due to the low level of damage specified; real grain prices are projected to decrease by 25% as world grain production rises to approximately 3.7 billion tons.

7. Significant Environmental Degradation

This scenario is functionally similar to the last, except that the damage parameter reaches a maximum level of 30% by 2050. Grain production in 2050 is predicted at close to 3.3 billion tons; paradoxically, rising real grain prices (up 22% over 50 years) spurred additional investment in agriculture and, realistically, greater land degradation, in a cycle of externalities characteristic of modern unsustainable shrimp farming systems.

While each of these scenarios presents a unique set of outcomes, there are an infinite number of possible combinations of assumptions that can be used in model runs, not the least of which might be combinations of the above cases. The theoretical case in which population growth is high, yield rates hit biological ceilings and unsustainable agricultural techniques deteriorate the quality of the land base is far from impossible, and likely tells a drastic story. The authors would be glad to run any scenarios so requested, but only so much space is available here.

XXIII. Conclusions

The predictions of this model vary widely depending on the initial assumptions underlying its forecasting, so it is important to recognize the breadth of the probability distributions associated with its various projections. However, relatively clear implications emerge from the union of these seven test cases.

First, in the case that moderate projections of technology and population growth (perhaps the center of the probability distribution of outcomes) we find conditions in the world food economy continuing to evolve favorably. Lower prices on world markets will increase the purchasing power of many of the poor in low income countries; increased production will provide a necessary, but not sufficient, condition for improving the welfare of many of the poorest in the world. However, it is important to note that in the real, imperfectly-competitive world economy, masses of peasant farmers in Asia and Africa may suffer from the downward trend in prices. It is also necessary to note that low prices are only one requisite for the elimination of hunger; if the poor do not have the incomes or the access to markets necessary to take advantage of low prices, hunger will remain.

Second, rapid population growth will provide a strain on the ability of supply to outpace demand. While case 3 did not forecast increasing prices, the interaction of high population growth with environmental degradation could easily produce price increases of levels that would be catastrophic for heavy grain importers.

Third, the importance of sustainable agricultural practices cannot be understated. The scenario which introduced the most drastic distortions by far was case 6; if current unsustainable agricultural practices are not altered in the near future, the interaction of soil erosion, land degradation, and a host of other negative effects have the capacity to reverse the positive trend of the last forty years.

Appendix A: Variable Definitions

Endogenous Variables[17]

(recall that subscript $_i$ exists in all variables other than prices)

Y_t	=	total production
$Y_{a,t}$	=	agricultural production
$Y_{na,t}$	=	non-agricultural production
I_t	=	total investment
$I_{a,t}$	=	agricultural investment
$I_{na,t}$	=	non-agricultural investment
$L_{a,t}$	=	agricultural labor force
$L_{na,t}$	=	non-agricultural labor force
Y_t	=	agricultural yield per hectare
$NX_{a,t}$	=	net agricultural exports
$NX_{na,t}$	=	net nonagricultural exports
$K_{a,t}$	=	agricultural capital stock
K_{na}	=	non-agricultural capital stock
$P_{a,t}$	=	agricultural price index
$P_{na,t}$	=	non-agricultural price index
$D_{a,t}$	=	demand for agricultural goods
$D_{na,t}$	=	demand for non-agricultural goods
μ_1	=	income elasticity of demand for agricultural products
μ_2	=	income elasticity of demand for nonagricultural products
λ_1	=	own-price elasticity of demand for agricultural products
λ_2	=	own-price elasticity of demand for non-agricultural products

Exogenous Variables

s_t	=	savings rate
N_t	=	population
g_t	=	rate of population growth
$g_{a,t}$	=	rate of technological progress
L_t	=	total labor force
A_{na}	=	level of non-agricultural total factor productivity
$A_{a,t}$	=	level of agricultural total factor productivity
δ_{gp}	=	decline in rate of population growth
δ_{ga}	=	decline in rate of technological progress
ε	=	labor force as a percentage of total population

[17] ~~Data sources for all series~~ include World Bank World Development Indicators 2001, FAO AGROSTAT

Model Parameters *(constant across i and t)*

ρ_1	=	degree of investment response to relative prices
ρ_2	=	degree of labor response to relative wages
$\delta_{k,a}$	=	depreciation rate of agricultural capital
$\delta_{k,na}$	=	depreciation rate of non-agricultural capital
$\acute{\alpha}_1$	=	elasticity of agricultural yield with respect to capital per hectare
$\acute{\alpha}_2$	=	elasticity of agricultural yield with respect to labor per hectare
$\acute{\alpha}_3$	=	elasticity of non-agricultural output with respect to capital
$\acute{\alpha}_4$	=	elasticity of non-agricultural output with respect to labor

Appendix B: Regional Breakdown

ex-Communist Bloc

Albania
Armenia
Azerbaijan
Belarus
Bosnia and Herzegovina
Bulgaria
Croatia
Czech Republic
Estonia
Georgia
Hungary
Kazakhstan
Kyrgyz Republic
Latvia
Lithuania
Macedonia, FYR
Moldova
Poland
Romania
Russian Federation
Slovak Republic
Slovenia
Tajikistan
Turkmenistan
Ukraine
Uzbekistan
Yugoslavia, FR (Serbia/Montenegro)

East Asia

Brunei
Cambodia
China
Hong Kong, China
Indonesia
Japan
Korea, Dem. Rep.
Korea, Rep.
Lao PDR
Macao, China
Malaysia
Mongolia
Northern Mariana Islands
Philippines
Singapore
Thailand
Vietnam

North America

Canada
Greenland
United States

Europe

Andorra
Austria
Belgium
Denmark
Faeroe Islands
Finland
France
Germany
Greece
Iceland
Ireland
Isle of Man
Italy
Liechtenstein
Luxembourg
Malta
Monaco
Netherlands
Norway
Portugal
San Marino
Sao Tome and Principe
Spain
Sweden
Switzerland
United Kingdom

South Asia

Bangladesh
Bhutan
India
Maldives
Myanmar
Nepal
Pakistan
Sri Lanka

Oceania

American Samoa
Australia
Fiji
French Polynesia
Guam
Kiribati
Marshall Islands
Micronesia
New Caledonia
New Zealand
Palau
Papua New Guinea
Samoa
Solomon Islands

Tonga
Vanuatu

Latin America

Antigua and Barbuda
Argentina
Aruba
Bahamas, The
Barbados
Belize
Bermuda
Bolivia
Brazil
Cayman Islands
Chile
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
Ecuador
El Salvador
Grenada
Guatemala
Guyana
Haiti
Honduras
Jamaica
Mexico
Netherlands Antilles
Nicaragua
Panama
Paraguay
Peru
Puerto Rico
St. Kitts and Nevis
St. Lucia
St. Vincent and the Grenadines
Suriname
Trinidad and Tobago
Uruguay
Venezuela, RB
Virgin Islands (U.S.)

sub-Saharan Africa

Angola
Benin
Botswana
Burkina Faso
Burundi
Cameroon
Cape Verde
Central African Republic
Chad
Comoros
Congo, Dem. Rep.
Congo, Rep.
Cote d'Ivoire
Djibouti
Equatorial Guinea
Eritrea
Ethiopia
Gabon
Gambia, The
Ghana
Guinea
Guinea-Bissau
Kenya
Lesotho
Liberia
Madagascar
Malawi
Mali
Mauritania
Mauritius
Mayotte
Mozambique
Namibia

Niger
Nigeria
Rwanda
Senegal
Seychelles
Sierra Leone

North Africa / Middle East

Afghanistan
Algeria
Bahrain
Cyprus
Egypt, Arab Rep.
Iran, Islamic Rep.
Iraq
Israel
Jordan
Kuwait
Lebanon
Libya
Morocco
Oman
Qatar
Saudi Arabia
Syrian Arab Republic
Tunisia
Turkey
United Arab Emirates
West Bank and Gaza
Yemen, Rep.

Somalia
South Africa
Sudan
Swaziland
Tanzania
Togo
Uganda
Zambia
Zimbabwe

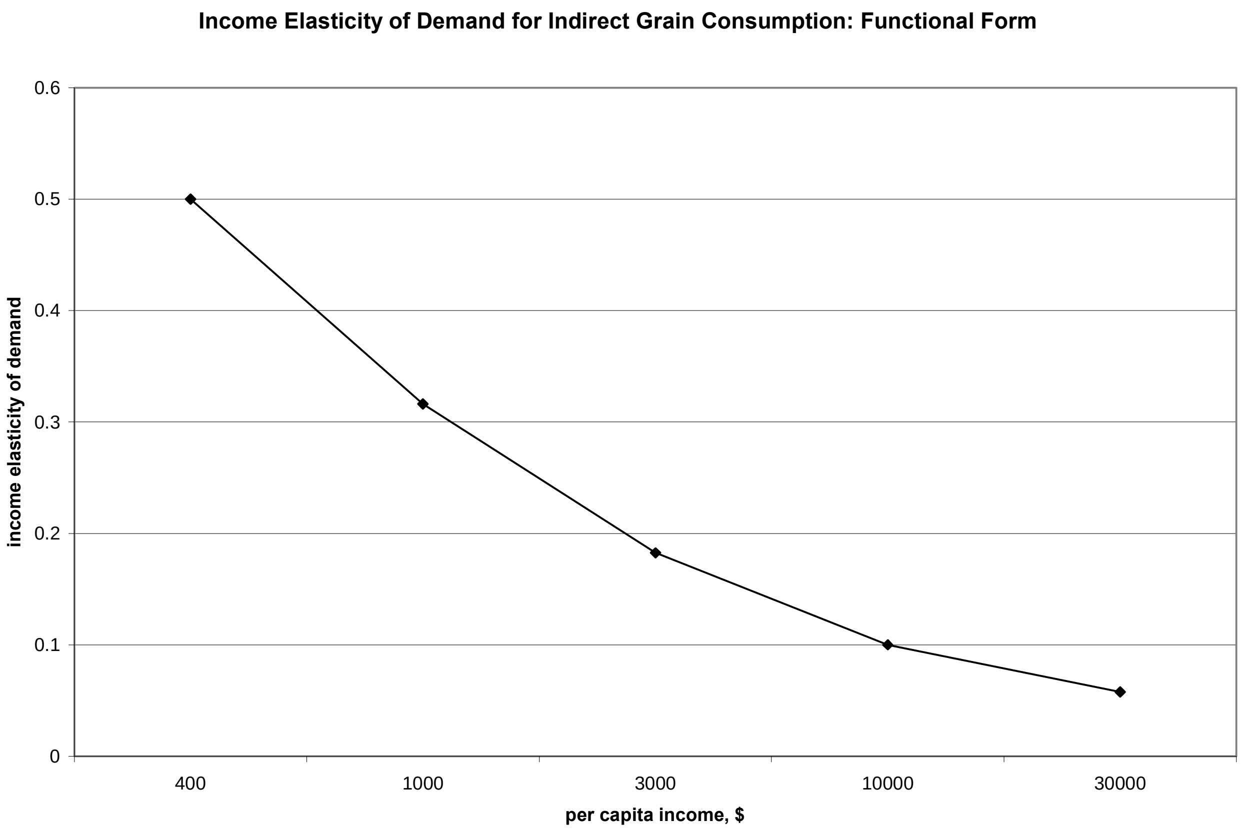
Appendix D[18]: Polynomial Approximations of Demand Elasticities

A model tracking regions over time within the world food economy must allow both price and income elasticities of demand to fall in absolute value as per capita incomes rise.

Following Weierstraus's theorem we can assume that any function can be approximated as a polynomial of the n^{th} order. The below functional forms are not overly controversial, but it is critical to note that panel data on the movements of demand elasticities over time are highly incomplete and that it is difficult to discern the accuracy of marginally different specifications.

Income Elasticity of Demand for Indirect Grain Consumption:

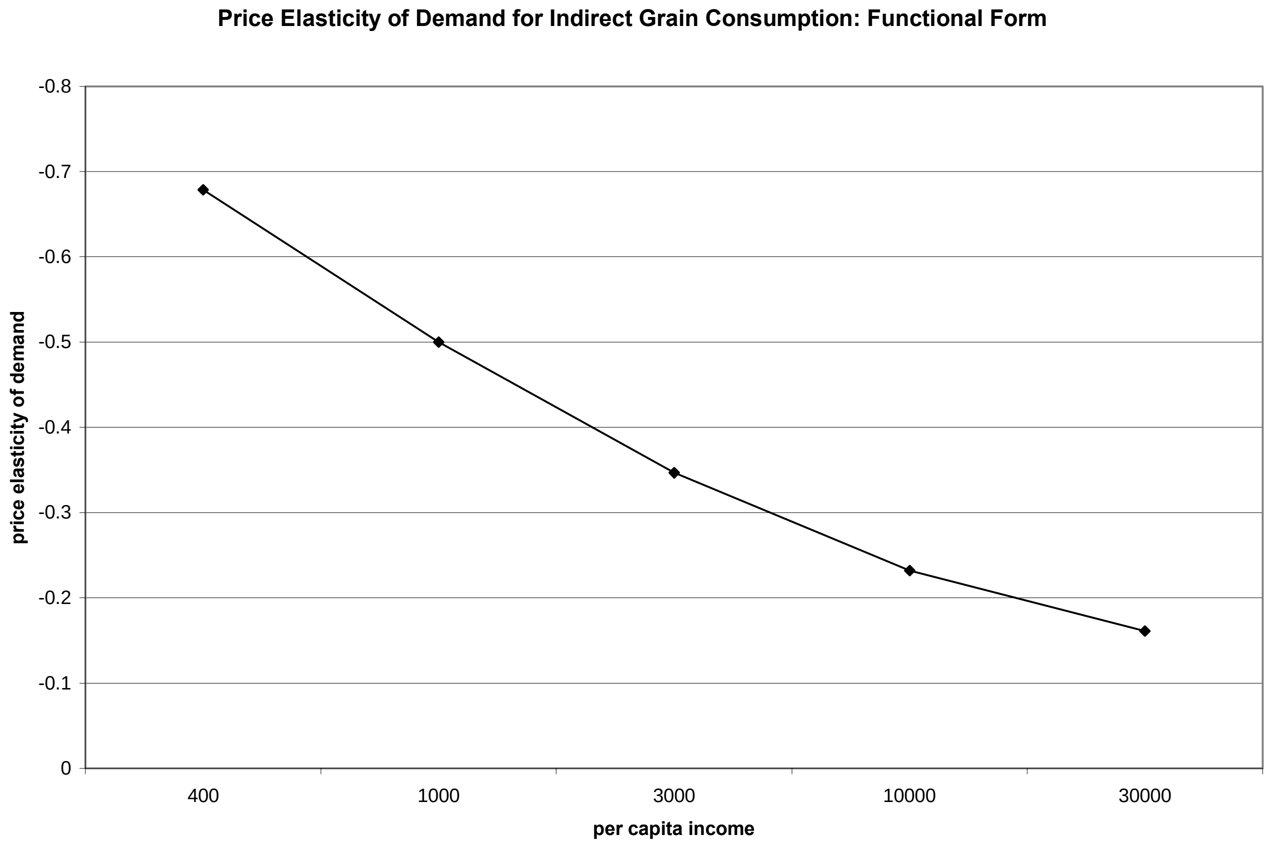
$$\eta_{i,d} \quad = \quad 10/(Y/N)^{\wedge}.5$$



[18] Please note: Appendix C includes graphs that cannot be displayed due to their size.

Price Elasticity of Demand for Indirect Grain Consumption:

$\eta_{i,d}$ = -5/(Y/N)^.33



Works Cited

FAO: *Agricultural Statistics Database*

Ester Boserup, *The Impact of Population Growth on Agricultural Output,* The Quarterly Journal of Economics, Volume 89, Issue 2 (May 1975)

H.R. Casas, *Imperfect Factor Mobility: A Generalization and Synthesis of Two-Sector Models of International Trade,* The Canadian Journal of Economics, Volume 17, Issue 4 (November 1984)

Gordon Conway, *The Doubly Green Revolution,* Cornell Press 1999

Yuiro Hayami and Vernon Ruttan, *Agricultural Development: An International Perspective*

W.A. Lewis, *Economic Development with Unlimited Supplies of Labor,* Manchester School, May 1954

Donald Mitchell, Merlinda Ingco, Ronald Duncan, *The World Food Outlook*, Cambridge University 1997

Mark Rosegrant, Michael Paisner, Siet Meijer, Julie Witcover, *Global Food Projections to 2020: Emerging Trends and Alternative Futures*, International Food Policy Research Institute 2001

S. Smidt and G.S. Tolley, *Agriculture and the Secular Position of the US Economy,* Econometrica, Volume 32, No. 4 (October, 1964)

World Bank: *Attacking Poverty*, 2000-2001

World Bank: *World Development Indicators 2001*