Effect of Biofuel on Agricultural Supply and Land Use

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> *History doesn't repeat itself, but it rhymes*
>
> —Mark Twain

Abstract While biofuels were introduced, in part, to reduce greenhouse gas emissions through replacing fossil fuels, comparing their impact to conventional sources has been difficult. This is largely due to the challenges of quantifying indirect land use change due to biofuels, which has proved controversial. This paper introduces a stylized, dynamic framework to analyze the evolution of land use expansion as well as deforestation over time. Our analysis suggests that land use change is a dynamic process and that relationships between variables are not regular over time and space. Technological change and effective environmental policy, of both agriculture and forests, can curtail deforestation. Outcomes of the model are illustrated with empirical data from the U.S. and Brazil. In the United States, deforestation does not lead directly to cropland expansion, as there is a transition period during which land is used as pasture or left idle. In Brazil, with four times more land in pasture or underutilized land than in cropland, there is significant potential for cropland expansion from this underutilized land.

Keywords Biofuels · Indirect land use change · Biofuel impact on agricultural supply

1 Introduction

The introduction of biofuels like corn and sugarcane ethanol was partially motivated by the desire to reduce greenhouse gas (GHG) emissions through replacing fossil fuels. However, the assessment of the GHG impacts of biofuel using lifecycle analysis (LCA) has proved to be quite challenging. The direct effects of carbon fuel

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M. Khanna and D. Zilberman (eds.), *Handbook of Bioenergy Economics and Policy: Volume II*, Natural Resource Management and Policy 40,
DOI 10.1007/978-1-4939-6906-7_7

on GHG emissions vary depending on the types of fuels used in production, processes used in producing each fuel, and the type and amount of fertilizer used in producing feedstocks (Farrell et al. 2006). Furthermore, Searchinger et al. (2008) suggested that in addition to the direct effects of biofuel production, there are indirect effects associated with the impacts of biofuel on commodity prices and the environment. He singled out indirect land use change (iLUC), which results from the introduction of biofuels, leading to higher prices of feedstocks that will likely lead to expansion of cropland acreage with a resulting decline in acreage for more environmentally friendly purposes (e.g., forestland).

Yet, the computation of iLUC has become controversial. In most cases, it was done using numerical simulation, either through computable general equilibrium (CGE) models, dynamic programming models, or partial equilibrium models (Khanna and Zilberman 2012). These studies vary significantly in their modeling approaches and estimation of parameters, and thus exhibit different results. The literature has realized that CGE has significant limitations, including arbitrary selection of model specifications and the selection of estimated parameters. In this paper, we assess the results of these models using a different approach. First, we develop a model to assess the inherent dynamics of the evolution of agricultural land use and its relationship to economic and technological factors. Second, we use empirical data from various sources to assess basic relationships between changes in agricultural commodity prices and agricultural land use. We find that the relationship between agricultural prices and land use at the extensive margin is *not regular* (namely that it cannot be reflected by a stable coefficient) while policy-makers and scientists are looking to obtain relationships that are *regular*.[1] For example, the gravitational coefficient g is regular and equal to 9.81 m/s^2 on Earth. On the other hand, indirect land use coefficients vary substantially between studies, and our conceptual analysis suggests that they are likely to change during periods of cropland expansion, but remain close to zero once total cropland has stabilized. They are affected by resource availability, regulation, inventory, technology, and demand. More fundamentally, the elasticities that are the life-blood of CGE modeling, which is used heavily in impact assessment, are not regular and reflect the changes over space and time, as mentioned above.

This paper presents a conceptual analysis and its outcomes are illustrated using empirical findings. The conceptual analysis consists of two sections: the first presents an optimal control model of optimal land allocation between agricultural land and the environment. This is followed by an analysis of the model, institutional and policy implications, and a discussion of other factors not included in the model that are likely to affect land allocation between agriculture and the environment. The model emphasizes the evolution and changes in land use in response to changes in demand and other parameters over time, reflecting the impacts of changing

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[1] They are regular in the sense that they produce outcomes that occur frequently under the same conditions (allowing some random errors that do not affect the average). For example, a constant elasticity reflects a regular relationship.

technology and the finiteness of land. The discussion demonstrates the importance of policy intervention in controlling processes like deforestation and effective management of land resources. The conceptual analysis as a whole suggests that elasticities of supply and demand for land and crops are likely to vary over time, and identifies considerations that are essential for realistic policy analysis. The empirical section of the paper will use data and observations from the U. S. and Brazil to illustrate how agricultural land use in these countries has evolved over time and how elasticities of aggregate land use with respect to crop prices vary in these countries based on cropland expansion and stabilization.

2 Conceptual Analysis

2.1 *The Basic Model*

Agricultural economists have long realized that locational heterogeneity in agro-climatic conditions impacts agricultural productivity. Studies on the history of agricultural production and the foundation of agricultural policy (Cochrane 1979; Schultz 1964; Olmstead and Rhode 2008) emphasize that trade-offs between the intensive and extensive margin and the increase in agricultural productivity has been a gradual process that involves expansion of land as well as changes in composition of inputs and their productivity.

Land is a unique resource whose quantity is finite, and its productivity varies across locations. There has been a large body of literature to understand the evolution of land use, land prices, and the impact each has on productivity (Lambin and Meyfroidt 2011). This analysis will rely on the literature on nonrenewable resources to assess the dynamics of land use. The total amount of land in a region is viewed as a finite resource, and economic development may entail conversion of wild land to agricultural production. We use the methods and techniques developed in Xabadia, Goetz, and Zilberman (2006) that models variation and land use patterns over space and time. Similarly, we initially solve for the socially optimal resource allocation over time and determine the policies that will lead to optimal outcomes for a competitive agricultural industry. Using this result, an allocation rule can be developed to determine when policies are suboptimal and should be modified. The derivation of the resource allocation rule under different conditions will help clarify how land use changes in response to changes in demand for output or to changes in other parameters.

2.2 *The Social Optimization Problem*

We assume that the objective of the social optimization problem is to maximize net discounted social welfare. The welfare measure at each period is the sum of benefits from consumption of biofuel and environmental amenities (associated with open space), minus the cost of production, R&D, and land conversion. The choices are constrained by the available technology, denoted by the production function, the evolution of technology as a result of investment in innovation, the dynamics of demand for agricultural output, and the finiteness of land resources.

Let output produced in period t be denoted by Y_t, so the aggregate production function at time t can be written as $Y_t = F(X_t, A_t, S_t)$ where X_t is the aggregate level of variable inputs used, A_t the amount of land available at time t, and S_t the stock of agricultural capital available at time t, measured in monetary terms. Agricultural land and agro-climatic conditions are heterogeneous, so the aggregate production of biofuel presented here may be interpreted as the aggregation of outcomes of micro-level optimization by multiple units subject to regional and behavioral constraints.[2] The capital stock variable reflects both human and physical capital, which is assumed to be given in the short run and accumulating over the long run. The increase in agricultural yields over time reflects that accumulation of capital is due to both private and public investment (Mundlak 2001), which will not be explicitly modeled in detail but discussed subsequently.

The investment in agricultural capital at period t is denoted by I_t and is measured in monetary units. The agricultural capital is growing according to $\dot{S}_t = \frac{\mathrm{d}s_t}{\mathrm{d}t} = I_t - \gamma S_t$, where γ is the depreciation of the capital stock. Agriculture is subject to increased vulnerability from evolving diseases, and some of the investment is used to maintain agricultural production.[3]

The agricultural land available for production must go through a process of conversion. The total land available in the region is $\bar{A}$, and the stock of land available for agricultural activity at time t is denoted by $A_t < \bar{A}$. The cost of land use is increasing at an increasing rate, and includes both land preparation and transportation. We denote this cost as $C(A_t)$, where $C_{A_t} > 0$ and $C_{A_t A_t} > 0$ where the subscript denotes the order and variable with which the derivative is taken.

We conduct a partial equilibrium analysis where social welfare at each period is the result of benefits from consumption of agricultural output and environmental amenities minus the cost of production and investment. The framework is very similar to Hochman and Zilberman (1986), but allows a more flexible functional form. The benefit from consumption at time t is denoted by B_t and is measured in monetary units. The total benefit is the area under the inverse demand curve, $B_t = \int_0^{Y_t} D^{-1}(\varepsilon, \propto_t)\mathrm{d}\varepsilon$, where $D^{-1}(\varepsilon, \propto_t)$ is the inverse demand function with quantity ε, and $\propto_t$ is the benefit shifting parameter at time t. The benefit function represents the area under the demand curve, and a higher $\propto_t$ can represent increases in demand for output, say grain, because of biofuel or population growth. It is assumed that the marginal benefit of $\propto_t$ is positive. Consumers also benefit from

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[2] This distinction results from the Cambridge controversies (Cohen and Harcourt 2003). Xabadia, Goetz, and Zilberman (2006) derived such relationship with a dynamic framework—expanding on the original aggregation of Houthakker (1955).

[3] Zilberman (2014) presents a framework for modeling agricultural systems that recognizes heterogeneity among producers, dynamic elements, and evolving pest damage.

environmental amenities provided by wilderness not converted to agriculture. The amount of wildland at time t is $E_t = \bar{A} - A_t$, and the value of the environmental benefits from wildland, in monetary terms, at time t is denoted by $V(E_t, \beta)$, where β is an indicator of environmental awareness (higher levels of β reflect higher awareness), so $V_\beta(E_t) \geq 0$. It is assumed the environmental benefits of wildlands are increasing at a decreasing rate, thus $V_E\left(E_{t,\beta}\right) \geq 0$ and $V_{EE}\left(E_{tt,\beta}\right) \leq 0$.

Using this notation, the objective function of the dynamic optimization is

$$\max_{Y_t, X_t, A_t, E_t, I_t, C_t,} \int_{t=0}^{\infty} e^{-rt}[B(Y_t, \propto_t) - w_t X_t + V(E_t, \beta) - C(A_t) - I_t]\mathrm{d}t \qquad (1)$$

Subject to:

$$\text{The production function constraint:} \quad Y_t = F(X_t, A_t, S_t) \qquad (2)$$

$$\text{The full land use constraint:} \quad E_t = \bar{A} - A_t \qquad (3)$$

$$\text{The equation of motion of agricultural capital:} \quad \dot{S}_t = \frac{\mathrm{d}S_t}{\mathrm{d}t} = h(I_t) - \gamma S_t \qquad (4)$$

As a starting point, we assume that the concavity of the benefit and production functions and the convexity of the cost functions hold, so that the necessary conditions of optimal control apply (Caputo 2005).

The temporal Hamiltonian to this optimization problem is

$$\begin{aligned} H_t = &\{B(Y_t, \propto_t) - w_t X_t + V(E_t) - I_t - C(A_t) + p_t[F(X_t, A_t, S_t) - Y_t] \\ &+ e_t[\bar{A} - A_t - E_t] + u_t[I_t - \gamma S_t]\} \end{aligned} \qquad (5)$$

where p_t is the shadow price of output, e_t the shadow value of environmental amenities produced on an acre of wildland, u_t the shadow value of expanding agricultural stocks by one unit at period t, and l_t the shadow value of expansion of land at period t.

The first-order conditions to this optimization problem are solved below where * defines the optimality outcome:

$$\frac{\partial H_t}{\partial Y_t} = 0 \Leftrightarrow B_{Y_t}\left(Y_t^*, \propto_t\right) = D^{-1}\left(Y_t^*, \propto_t\right) = p_t^* \qquad (6)$$

$$\frac{\partial H_t}{\partial X_t} = 0 \Leftrightarrow p_t^* F_{X_t}\left(X_t^*, A_t^*, S_t^*\right) = w_t^* \qquad (7)$$

$$\frac{\partial H_t}{\partial E_t} = 0 \Leftrightarrow V_{E_t}\left(E_t^*, \beta\right) = e_t^* \qquad (8)$$

$$\frac{\partial H_t}{\partial A_t} = 0 \Leftrightarrow p_t^* F_{A_t}\left(X_t^*, A_t^*, S_t^*\right) = e_t^* + C_{A_t}\left(A_t^*\right) = V_{E_t}\left(E_t^*\right) + C_{A_t}\left(A_t^*\right) \tag{9}$$

$$\frac{\partial H_t}{\partial I_t} = 0 \Leftrightarrow u_t^* = 1 \tag{10}$$

$$-\frac{\dot{\partial} H_t}{\partial S_t} = \dot{u}_t^* - r u_t^* \Leftrightarrow \dot{u}_t^* = (r+\gamma)u_t^* - p_t^* F_{S_t}\left(X_t^*, A_t^*, S_t^*\right) \tag{11}$$

Equation (6) shows that at the social optimum, output is selected to meet the level required by demand. According to Eq. (7), variable input used in each period is at the level where the value of its marginal product is equal to its price. Equation (8) states that when land is allocated optimally to environmental activities, the shadow price of land is equal to the marginal value of environmental amenities provided by the land. Equation (9) states that the optimal allocation of land to agriculture occurs when the value of the marginal product of production minus marginal cost of land is equal to the shadow price of land, or put differently, when the value of output from the land is equal to the marginal cost of the land plus the marginal benefits of the environmental amenities provided by the land when not farmed agriculture. Equation (10) states that optimal investment in capital at time t should be where the social marginal value of the output it generates is equal to the marginal cost of investment (which is \$1 since investment is in monetary terms). Finally, condition (11) states that the temporal shadow price of the stock of agricultural capital changes over time so that growth in the shadow price of capital over time is equal to its shadow price multiplied by the sum of the discount and depreciation rates minus the value of the marginal product of agricultural capital. The reason for this condition is that delay in employing a unit of capital in production will enable gains from interest in alternative uses and will delay depreciation, but will lead to a loss of the output the capital would have produced during the period of the delay. Equations (6)–(11) and the early Eqs. (2)–(4) form the optimality conditions. The optimal path also includes the initial stock of agricultural capital S_0 and that the discounted shadow price of increasing agricultural capital reaches 0, as shown by the $\underset{t \to \infty}{\text{limit}} e^{-rt}u_t = 0$.

2.3 *The Implications of the Model*

Due to space limitations, we will not analyze the outcome formally through rigorous tools of comparative dynamics (Caputo 2005), but rather analyze the changes implied by the individual first-order conditions to approximate the direction of changes in key variables in response to changes of key parameters. In particular, we are interested in impact of changes in demand (larger $\propto_t$) and changes in environmental preferences (larger β) on the socially optimal outcomes.

1. **The impacts of a larger** $\propto_t$: Eq. (6) suggests that increase in demand for output will increase $D^{-1}(Y_t, \propto_t)$, and thus output price p_t, at least in the short run. Higher output price in the short run will lead to increased input use intensity [based on Eq. (7)], increased land use [as long as the land constraint is not binding, based on Eq. (9)], and increased investment (since the gain from future agricultural capital use increases).[4] Increased investment may increase capital accumulation over time (higher levels of S_t for $t > t_\alpha$ where t_α is the moment at which the demand increases). The larger agricultural stocks in the longer run (at some time $t > t_\alpha$) may lead to a partial reversal of the short-run effect—lower output prices, less variable input use, decline in overall land use, and slower investment.
2. **The impacts of a larger appreciation of environmental amenities** ($\boldsymbol{\beta}$) **(from a certain** $\boldsymbol{t \geq t_\beta}$): According to Eq. (8), the immediate effect of this change may be to reduce land in agriculture.[5] The reduction of agricultural land because of higher β will increase output prices, increase variable input use, and may lead to further investment. In the longer run, higher investment increases agricultural capital and reduces output prices, which may counter some of the increase in variable input use but actually expand the reduction in land use if capital and land are substitutes.
3. **The impact of demand shifts on the dynamics of output**: Both $\propto$ and β affect the dynamic path of the optimal solution. If they are constant over time, the production and utility functions are concave in all inputs and the cost function is convex, the standard optimality conditions hold, and the model is likely to have a stable steady state (Caputo 2005). However, we assumed that $\propto_t$ is growing over time to represent population growth as well as the introduction of biofuels. β may increase as well due to heightened awareness of the benefit of environmental amenities. The increase in $\propto_t$ will raise prices, so output will increase over time. The increase in demand will also lead to an increase in investments, which will increase the capital stock, tending to reduce prices. One major issue in our analysis is the effect of agricultural capital on productivity. Historically, the increase in agricultural capital because of both public and private sector investments led to very large increases in output, which actually resulted in prices declining over time (Schultz 1964). There may be an element of increasing returns to scale in capital, and a more rigorous analysis may apply in some of the tools and thinking that was developed to address the economics of

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[4] Higher output price leads to lower gains from delaying the introduction of capital, since $\dot{u}_t = (r+\gamma)u_t - p_t F_{S_t}(X_t, A_t, S_t)$ declines over time and investment become more valuable. The increase in output price has the same qualitative effect as a reduction in interest rate, namely increased investment.

[5] Unless we are at a corner solution where all the land is in farming, as the increase in β is not sufficient to lead to conversion of land back from farming to wilderness.

increasing returns to scale (Arthur 1996). Thus, the relationship between output, land use, and variable input use is evolving over time, even under our optimal scenario. Given the difficulty in measuring capital, it is very unlikely that this relationship can be captured by a few stable or regular elasticities.

The analysis thus far has assessed the changes in optimal behavior with respect to biofuel production. The first-order conditions provide a benchmark to obtain many useful insights and analyze plausible scenarios. But outcomes in reality may deviate significantly from the optimal outcome. The economy may exhibit competitive behavior without any interventions to protect the environment or ensure the provision of public goods. Yet, comparison of such an economy with optimal outcomes can provide some key lessons. In particular:

1. **The importance and value of governance**—The optimal outcome may be obtained with a government that imposes: (i) an environmental policy (taxes, zoning, subsidies) where the de facto price of the land providing environmental amenities at each period is equal to e_t, and (ii) the appropriate support for R&D. The private sector will invest in private agricultural capital, but government intervention to finance public R&D is needed to complement it in order to provide the optimal $I_t = I_t^*$ in each period. An important exercise is to assess the social welfare under the optimal outcome versus a *laissez faire* regime.
2. **Likely underinvestment in agricultural capital**—There is a large literature documenting and analyzing the underinvestment in public research in agriculture. This underinvestment can be mostly explained by political economic reasons (Rausser, Swinnen, and Zusman 2011). In developed countries, total R&D expenditure has not declined over time because private sector investment increased during periods of decline in public sector spending. However, the literature suggests that public and private sector spending are not substitutes, rather they are complements, and thus the decline in public sector investment suggests overall underinvestment in research (Alston, Beddow, and Pardey 2009). In developing countries, the degree of underinvestment is more pronounced (Bell and Pavitt 1997). Underinvestment in agricultural research $(I_t < I_t^*)$ may lead to suboptimal levels of agricultural capital, slow increases in output, and a decline in prices over time.
3. **Likely overuse of land**—Assuming that during an initial period there is no enforcement of environmental policies ($e_{t_0} = 0$), and that there is low initial agricultural capital and underinvestment in agricultural capital such that $S_t < S_t^*$, the allocation choice of land in that period is determined according to:

$$p_t F_{A_t}(X_t, A_t, S_t) = C_{A_t}(A_t) \tag{12}$$

Comparison of Eq. (12) to Eq. (9) suggests that the likely lower marginal cost of land without government intervention will result in overuse of land for agricultural purposes, namely $A_t^* < A_t$. In some cases, it will result in agricultural settling of all the arable land so that after some point in time t_1, $\bar{A} = A_t$. The large amount of deforestation that occurred historically in older and population-intensive civilizations like Europe, China, and India may reflect centuries of growing demand, minimal environmental protection of wildland, and low technological progress. The settlement of the United States from coast to coast in the nineteenth century also reflects similar tendencies (Cochrane 1979), and much of the intensification of U.S. agriculture occurred after most of the continent was settled.[6]

Our discussions thus far suggest that introduction of environmental policies and expanded investment in agricultural R&D may actually lead to decline in total agricultural land. The idea that investment in research may lead to actual reduction in agricultural land is well known, and was previously suggested by Cochrane (1979). Cochrane (1979) also suggested that agricultural land in the United States reached a peak in 1920, and innovations and conservation programs led to smaller agricultural acreage levels throughout most of the twentieth century. Without concern about the environmental side effects of agriculture and technology that lead to intensification, population growth is likely to lead to expansion in agricultural land use and possibly deforestation (Binswanger and Mcentire 1987).

2.4 Going Beyond the Original Model

The formal model presented above simplifies primary features of the system to explain some key elements of the dynamics of land use. To develop a more complete understanding of reality, we discuss complexities and variations and their implications less formally.

1. **The difference between clearing of land and establishment of a farming system**. In our analysis, it is assumed that the transition from wildland to agricultural land is instantaneous. But, the reality is more complex—deforestation activities in many cases can occur instantaneously, but the conversion of forestland into productive agricultural land may take a long period of time. Geist and Lambin (2002) found that the purpose of deforestation might eventually be for agricultural settlement, wood use, and expansion of infrastructure, among other reasons. Wood has been a major source of energy for millennia and was a major cause of deforestation. The first wave of land use change involves clearing forests and using the wood for fuel or other purposes. Next, individuals begin deforesting land in order to start farming it extensively and establish property rights, which will enable them to benefit from more intensive use in the future (Southgate 1990). In those cases, land may be used as pasture before it is converted for intensive crop production. The original model can be developed along the lines of Southgate (1990) to account for these time delays. A major

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[6] In this case, there were political reasons for fast settlement.

point emphasized in our model that resonates with both Southgate and Geist is that intensive deforestation occurred mostly because of a lack of enforcement, as deforesters often did not pay the social cost of cutting the trees, but received the immediate benefits from its use. In cases where there is a time gap between significant agricultural utilization of land and deforestation, one may expect to see large amounts of land that are denoted as pastures or undeveloped land.

2. **Transportation costs**. We assume that marginal costs of production are increasing with acreage, and that may correspond to a situation where as acreage increases, transportation costs to an urban center or port is increasing. But, we did not explicitly consider the cost of transportation over space and how the costs of transportation may change over time as a result of investment and infrastructure development. For example, the building of railroads and waterways in the United States were crucial in the development of farming in the Midwest (Nichols 1969). Without sufficient infrastructure, roads, processing facilities, etc., development of intensive agriculture in frontier regions may be limited. Thus, more complete analysis of the relationship between agricultural output prices and land use may require taking into account the investment and time required to expand transportation systems as well as consider the constraints on land use expansion because of transportation costs.
3. **Variability**. Our analysis assumes homogenous, identical inputs as well as full certainty. However, Lichtenberg and Zilberman (1988) suggested that economic choices are affected by variability, which may include random events such as inclement weather, heterogeneity, and lack of knowledge. Timing of land use is affected by variability over time, both in terms of climate and economic conditions. Dixit and Pindyck (1995) suggested that the randomness of prices and other variables are considered in investment decisions, and that new investments are not made based on profitability under average conditions, rather when the profitability level is sufficient to overcome a hurdle that represents the cost of the uncertainty involved. Thus, their analysis suggests that uncertainty about economic conditions and other factors may serve to delay land use choices. Heterogeneity also affects land use patterns. Specific topographic and climatic conditions may affect where, how, and to what extent land use change occurs, and topographic barriers may set limits to such changes. Finally, knowledge and technology are also crucial in affecting the dynamics of land use changes. For example, the discovery of a new technology that utilizes wood may accelerate deforestation processes.
4. **Inventory considerations**. Our analysis assumes that output prices clear instantaneously, but major agricultural commodities are storable and random forces of weather and disease affect their supply. Thus, consumption and production choices as well as prices are affected by these inventory levels. When there is an increase in demand and inventories are low, prices will increase drastically, which may trigger increases in supply, including expansion of land use, which is much more significant than when inventories are sufficient (Wright 2011). Hochman et al. (2014) argue that the expansion of biofuel regulation in 2008 resulted in a large price effect because of the low level of inventory, and

Wright (2014) emphasized that the price increase was compounded by the effect of low inventory and expectation of higher prices in the future because of the biofuel mandate. These implications suggest that the dynamics of production and prices are affected by inventory availability and policy.

5. **Reforestation**. We assume that β is an indicator of environmental preference and that it may change over time. For example, as countries get richer, there is higher willingness to pay for environmental amenities. If this occurs, the optimal acreage allocated to agriculture may decline after it reaches a peak, and we may witness a phenomenon where land will be reallocated to wildland. This corresponds to observed situations in reality where there is reforestation. Our conceptual framework suggests that these situations are more likely to occur when the increase in β is combined with large increases in productivity and relatively low increases in demand.
6. **Political Considerations**. The analysis thus far reflects optimal choices by economic agents. But, land use decisions reflect policy choices by governments. Governments may elect to design institutions, build incentives, and encourage projects to expand the land they control. Design and construction of the railroads in the U.S. as well as the Homestead Act that provided people the right to land they settled were part of a large scale settlement in the U.S., among other projects (Cochrane 1979). The Brazilian government took initiatives to develop land in the Amazon, including developing a homesteading system and building the trans-Amazon freeway (Moran 1981). The Brazilian government also invested a significant amount in agricultural research infrastructure that resulted in soybean varieties that can grow under the agro-ecological conditions in Brazil. These development activities were conducted with the intention of developing millions of hectares of land. The expansion of soybean in Brazil combined R&D investment a significant amount of subsidies with a vision to expand close to one hundred million hectares of land, most of it outside the Amazon (World Development Report 1986; Goldsmith and Hirsch 2006; Warnknen 1999). Freire de Sousa and Busch (1998) emphasize the role of investment in R&D in establishing the Brazilian soybean industry, and argue that as a technology develops and settlement expands, networks of support for the nascent industry are established, which propel its growth even further.
7. **Distinguishing between short and long-term land expansion decisions**. Our discussion of possible expansions of the model has one common theme: there is a distinction between activities that result in long-term commitments and short-term choices. For example, the construction of a railroad, investment in research that results in new varieties, or investment in processing centers and land improvement are the major land use choices that establish long-term supply that allows short-term decisions to be made by comparing immediate revenues to costs. Much of the long-term expansion of agricultural capacity that drives the settlement process is determined as the result of long-term vision that takes into account long-term predictions as well as political considerations, and may not necessarily be affected by short-run fluctuations. Thus, settlement processes were motivated by both individual long-term profitability as well as desire for

> political expansion and economic development, but were constrained by either technical or financial feasibility, and in particular land availability and awareness of the value of alternative uses of the land in conservation or environmental amenities. Short-term considerations might affect the timing of execution of expansion activities as well as specific selection of crops and intensities.

Analysis of the model and its limitations has significant implications for analyzing land use changes associated with increases in demand. Because the amount of land available is finite, even under the simple formulation of the model, the rate of change of conversion of land to farming may vary over time depending on how much land has been developed and how much is left for possible development. It will also be affected by long-term investments in infrastructure and technology as well as regulation and market conditions. When agricultural expansion is profitable, land availability may be the driving constraint on expansion unless environmental regulations are introduced and enforced.

The numerical exercises that aim to calculate indirect land use through general partial equilibrium models or other simulations (Khanna and Zilberman 2012) assume that the integrated economic and agro-biophysical systems have regularity that can be captured relatively well through statistical means. The parameters of the systems are assumed to be regular, stable over time, and able to be estimated statistically to provide reliable predictions. For example, many of these models assert a constant elasticity or a consistent relationship between two variables of interest. However, our analysis thus far suggests that the process of land use change is dynamic and the parameters that reflect land use change may not be regular. It is a process with a beginning and an end that may evolve at a different pace over time and be represented by coefficients that also change over time. These changes in parameters may reflect omitted factors that introduce biases. Therefore, our conceptual model and discussion suggest that estimating stable and regular coefficients to capture the basic parameters of indirect land use may be challenging, and in many cases, not feasible. It suggests that coefficients of land use vary significantly with the method of estimation, location, and period of time.

3 Empirical Analysis

There are several bodies of evidence that support some of the major conclusions of our conceptual model. In particular, we will present evidence that shows that the agricultural acreage in developed countries will start to plateau over time, and only in regions where development is rising. Figure 1 shows the agricultural acreage in the United States. It shows that land in farms, including both pastures and cropland, reached a peak in the 1950s (Alston et al. 2009). Furthermore, cropland in the United States peaked in the 1920s, and during the post war period it increased and declined with the ebb and flow of agricultural business cycles (Cochrane 1979).

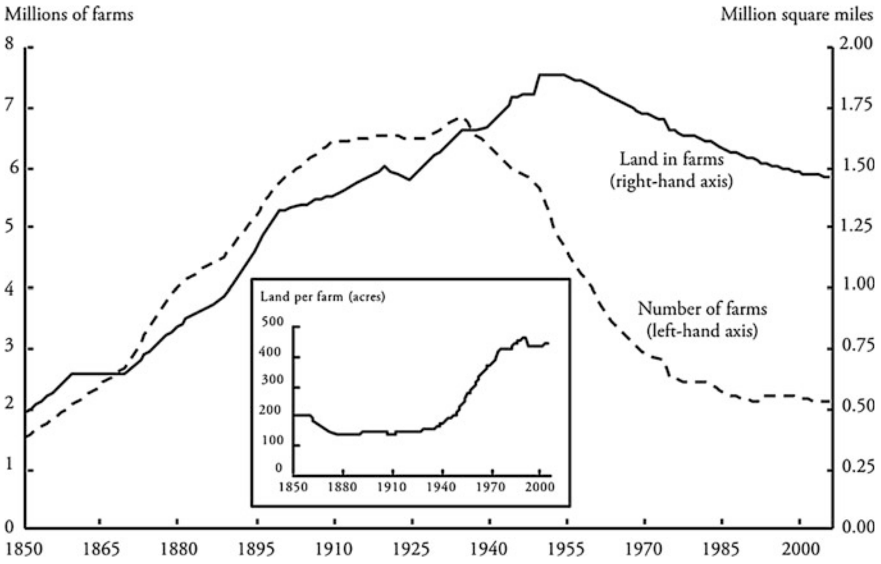

Fig. 1 United States Farmland Trend from 1850 to 2000; *Sources* Number of farms (1910–1999) and Land in farms (1911–1999) are from Olmstead and Rhode (2008, series Da 4 and Da 5, respectively). For both variables, values for 2000–2006 are from USDA ERS (2007); 1900 and 1890 values for farm numbers are from the U.S. Bureau of the Census (1975, series K-4 and K-5); 1910, 1900, and 1890 values for land in farms are from series K-5 of the same resource. *Notes* For farm numbers, intercensus values were estimated using a linear interpolation wherever no value was provided

Cochrane as well as Schultz also argue that in response to food shortages and increased demand in agriculture over the past century, in the short-term prices increase and crop acreage increases on the margin, but higher prices lead to investments in capital goods and increases in productivity, which leads to overshooting of demand and results in lower prices that reduce agricultural acreage on average (as shown in Fig. 2).

Furthermore, Goldewijk et al. (2004) analyzed land use change over the last 300 years and found that acreage of global agricultural cropland has expanded since the 1700s. As our model predicts, there are changes in regime once an implicit land availability constraint is binding. However, in the old world (Europe), acreage reached a peak in the 1920s and in new developed countries (United States, Canada, Australia) it reached a peak in the 1950s, but in the developing world, agricultural acreage continues to grow, as seen in Fig. 3 (Goldewijk et al. 2004). The land availability constraint is a result of both physical constraints and regulatory limits. We are aware that production in the Old World continues to grow significantly beyond the peak of acreage, and the same is true in the new developed countries like the United States and Australia (the countries that produce much of the world's food). In these countries, intensification was the main course of action to increase food supply, and sometimes, as Schultz and Cochrane argue, increases in

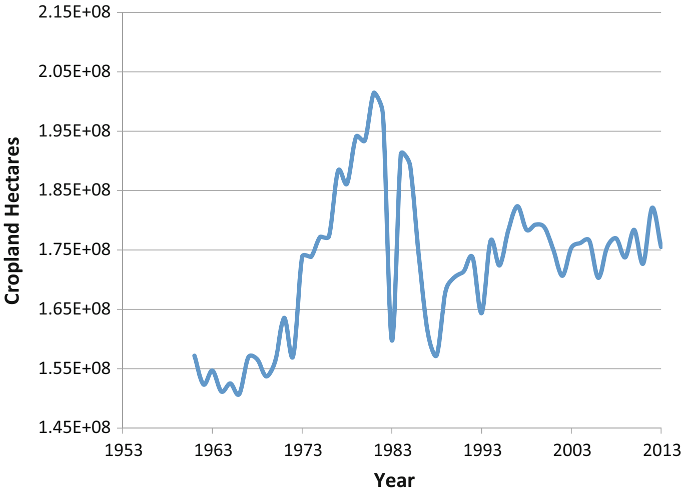

Fig. 2 Agricultural Acreage Trends in the United States from 1961 to 2013 *Source* Authors own aggregation from the Food and Agricultural Organization of the United Nations (FAO)

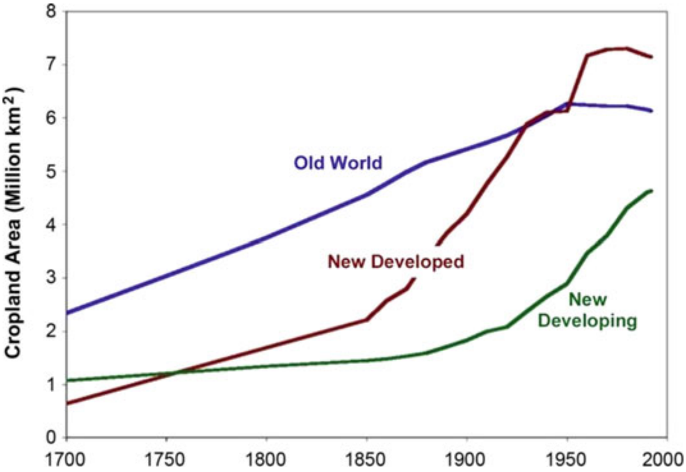

Fig. 3 Cropland trends in the developed and developing worlds *Source* Goldewijk et al., (2004)

productivity will outpace increased demand, causing agricultural acreage in these countries to decline. In the developing world, agricultural acreage continues to grow because of lack of environmental regulation and lack of investments in and capacity to increase intensification.

More refined analysis of land use change since the industrial revolution is shown in Table 1 (Goldewijk et al. 2004).

Table 1 Land use change by different types of land between 1700 and 1990

Reference year	Forest/woodland	Steppe/savanna/grassland	Shrubland	Tundra/hot desert/ice desert	Cropland	Pasture	Total
Klein Goldewijk (2004)							
Undisturbed	58.6	34.3	9.8	31.4	0.0	0.0	134.1
1700	54.4	32.1	8.7	31.1	2.7	5.2	134.1
1850	50.0	28.7	6.8	30.4	5.4	12.8	134.1
1990	41.5	17.5	2.5	26.9	14.7	31.0	134.1

Source Goldewijk et al. (2004)

As the table suggests, between 1700 and 1990, agricultural land increased by 37.8 million km^2 (from 8.1 to 45.7 million km^2). This change includes deforestation (12.9 million km^2), conversion of grassland (14.6 million km^2), shrubland (6.2million km^2), and tundra (4.2 million km^2). However, more than 2/3 of agricultural land is pasture (31 million km^2) while less than 1/3 is cropland (14.7 million km^2). More than twice as much of the converted land from its natural land uses was used as pasture, and much of the pasture is used extensively (i.e., much of the conversion of natural land uses was not to increase cropland, but to take advantage of the wood and other resources). The conversion to pasture was either because of the low productivity of the land as cropland or as a transitional state that would enable assumption of ownership of the land (Southgate 1990).

As Table 2 suggests, Brazil is an example of a country where most of the arable land is either in pasture or is available for agricultural production. Less than 20% is used for crop production and there is a large acreage in grazing, which is mostly done extensively. If there is a need to increase agricultural production when environmental regulations are enforced, it can come from conversion of rangeland to cropland, rather than deforestation.[7]

Obviously, increases in food prices make conversion of land to cropland more attractive. But in many parts of the world, most agricultural land reaches its peak and much of the conversion of land for agriculture was by nonagricultural uses. In particular, the major cause for the conversion to cropland was not the profitability of agriculture, but the fact that the economic and regulatory barriers to conversion were minimal.

Further evidence supporting our model was found in Swinton et al. (2011) and Barr et al. (2011). Swinton et al. (2011) estimated that between 2006 and2009, a 64% increase in profitability of agriculture increased acreage in the Midwest by only 2%. Their analysis implies a land elasticity with respect to profitability of 0.03,

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[7] There may be some GHG emissions from conversion of rangeland to cropland, but it depends on cultural practices (Lal 2002). For example, use of low or no tillage can minimize it, and in some cases can even help to rebuild the carbon stock in the soil.

Table 2 Land use in Brazil

Millions of hectares			% of Brazil	% of arable land
Brazil		**851.4**		
Total arable land		**329.9**		
1	Crop land—total	**59.8**	***7.0***	***18.1***
	Soybean	21.6	*2.5*	*6.4*
	Corn	14.4	*1.7*	*4.4*
	Sugarcane	8.1	*0.9*	*2.5*
	Sugarcane for ethanol	**4.8**	***0.6***	***1.5***
2.	Pasture land	**158.7**	***18.6***	***48.1***
3.	Protected areas and native vegetation	**495.6**	***58.2***	–
4.	Available area	**137.2**	***16.1***	–

Source IBGE (2011). Produção Agrícola Municipal. Instituto Brasileiro de Geografia e Estatística

which reflects farmers' reluctance to increase the land base because of implicit high marginal costs. They view it as a constraint in the introduction of second generation biofuel through expansion of the agricultural land base. Barr et al. (2011) estimated the elasticities of land use with respect to expected returns and implied agricultural commodity prices in the U.S. and Brazil. Like most of the literature that studies the elasticity of acreage of specific crops (e.g., soybean and corn) with respect to changes in returns or price, they study the elasticity of total acreage following the insight of Galbraith and Black (1938), namely that the elasticity of demand for land with respect to output price or profit is high, but that change in *total acreage* is much less elastic. It is surprising that despite the importance of these observations, no one until Barr et al. (2011) has attempted to verify it using recent data. Table 3 is based on their paper, and derives the elasticities of total agricultural acreage in the U.S. with respect to (w.r.t.) expected returns and agricultural commodity prices. As one can see, this elasticity is very low, reflecting what both our theory as well as Fig. 1 suggests.

The data from Brazil is more interesting. As Table 4 suggests, the elasticity of total crop acreage with respect to both returns and agricultural commodity prices is quite high, even though it has declined over the last 10 years. These elasticities are much higher compared to those in the United States, suggesting that crop acreage in Brazil is continuing to expand. As our theoretical model suggests, during a period of agricultural expansion, the elasticity is positive but not necessarily constant. The

Table 3 Elasticity of Land Use in the United States

		2003–05 to 2007–09	2004–06 to 2007–09	2007–09 trend to 2007–09 actual
United States	Acreage elasticity w.r.t. expected returns	0.005	0.014	0.028
	Implied acreage elasticity w.r.t. implied price	0.007	0.020	0.029

Table 4 Elasticity of Land Use in Brazil

		1997–99 to 2001–03	1997–99 to 2001–03 (2-year lag for land)	2004–06	2006–09
Brazil	Acreage elasticity w.r.t. expected returns	0.330	0.444	0.162	0.192
	Implied acreage elasticity w.r.t. implied price	0.664	0.895	0.382	0.477
Brazil (including pasture)	Acreage elasticity w.r.t. expected returns	0.100	0.122	0.003	0.033
	Implied acreage elasticity w.r.t. implied price	0.201	0.245	0.007	0.082

elasticity is close to zero when agricultural cropland has more or less stabilized, as is the case in the United States.

But, to gain a better understanding of the process of deforestation in Brazil, one must consider the elasticity of total agricultural land, including pasture, with respect to expected returns and crop prices. These elasticities of total agricultural land, including both cropland and pastures, are smaller than the elasticities of cropland with respect to expected returns and prices. Moreover, these elasticities decline significantly in the new millennium compared to the 1990s, despite the rise in the price of agricultural commodities. This result suggests that the expansion of agricultural land is mostly occurring into pasture, supporting our previous analysis that the deforestation process does not necessarily consist of immediate conversion of wildland to cropland, rather there is a transition period such that this land is converted to pasture. Furthermore, the decline in the elasticity of total agricultural land with respect to commodity prices since the new millennium suggests that the decline in conversion of wildland, including forests, into agricultural land (mostly pasture) occurred during a period when Brazil enforced stricter environmental laws to curb deforestation and commodity prices were rising. This suggests that an effective way to curtail the process of deforestation is to make it costly by instituting and enforcing strong forest and wildland protection laws.

Thus, if one is interested in assessing the impact of biofuel or similar activities that extend use of agricultural land, they should use the elasticities obtained by Barr et al. (2011) or similar studies that estimate elasticities of overall land conversion with respect to changes in commodity prices. Their low magnitudes as well as the aggregate data presented previously suggest that the effect of increasing commodity prices because of biofuel and other activities is minimal in mature countries as well as in growing countries that introduce effective environmental regulation.

One may argue that without the introduction of biofuel, the processes of reforestation would have advanced further, and thus biofuel may slow or reverse these processes, which may be the case. However, the process of reforestation is occurring because of the increase in the profitability of agriculture that leads to further innovation and enhancement of productivity per acre, and thus the increase in productivity induced by biofuel may eventually lead to contraction of the land base to the most productive land. The net effect is not clear, and we do not have a quantitative estimate for regulating the indirect land use effect of biofuel. But, it is clear that policies restricting the introduction of technologies that enhance agricultural productivity per acre do not help reforestation processes.[8]

4 Conclusion

This paper introduces a stylized, dynamic framework to analyze the evolution of land use expansion as well as deforestation over time, and suggests that given a finite amount of land and some social benefit from wilderness, the process of land expansion is of finite length, and as an economy matures, it will reach its peak and stabilize. This peak level will be determined by growth in demand, rate of technological change, and preference for environmental amenities. As technological change and environmental preferences begin to increase faster than increases in demand, the acreage in crops in the long run will decline, and in some cases may be associated with reforestation.

Empirical data appears to support the major implications of the conceptual model. Total crop acreage in the U.S. and Europe has already peaked, and has actually declined in recent years, while agricultural acreage in developing countries continues to increase. But, further analysis suggests that deforestation is not likely to lead directly to cropland expansion, but that there is a period of transition between deforested land and conversion to cropland where the land is either idle or used for pasture. In countries like Brazil, there is four times more land in pasture or that is underutilized than in cropland, suggesting significant potential for cropland expansion from pastures or underutilized land. Since the turn of the century, stricter environmental regulation was introduced in Brazil, and the total agricultural acreage, including cropland, has become much less responsive to changes in agricultural crop prices, suggesting that a major tool to slow deforestation is for the government to change deforestation policies. Deforestation declines if expansion of the land base is not an explicit objective of government policies as well as if there are forceful mechanisms to curb deforestation activities. The analysis suggests that it is unlikely to have a regular land use coefficient that can be utilized for a long period of time in policy analysis, and that effective environmental policy can curtail deforestation while increased agricultural prices will instead lead to intensification.

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[8] For example, the banning of GMOs. Barrows et al. (2014) demonstrate how the introduction of GMOs actually reduce the carbon footprint of agriculture.

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