University of California, Berkeley
Department of Agricultural &
Resource Economics

CUDARE Working Papers

Year 2010 *Paper 1100*

The Economics of Trade, Biofuel, and the Environment

Gal Hochman, Steven Sexton
and David Zilberman

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Gal Hochman †

UC Berkeley

Energy and Bioscience Institute

Steven Sexton‡

UC Berkeley

Department of Agriculture and Resource Economics

David Zilberman§

UC Berkeley

Department of Agriculture and Resource Economics

March 11, 2010

Abstract

The introduction of renewable biofuels was associated with global food crisis and unintended environmental consequences. This paper incorporates energy environment and agricultural sector to the classic Hecksher-Ohlin model to address these issues. A household production function model was introduced to model consumer energy choices and concern about externalities related to climate change and open space. The conceptual model links energy and food markets and derives guidelines for the development of climate change and land-use policies. The results suggest that globalization and capital flows increase demand for energy, leading to decline in food production, increase in food prices, and loss of environmental land. Globally optimal outcomes may require introducing an emission tax and a land-use tax. The introduction of these policies may undermine the factor price equalization theorem. Policies that allow enhancing either agriculture productivity (e.g., agriculture biotechnology) or biofuel productivity (e.g., second-generation biofuels), are shown to lessen the resource constraint associated with the cost of introducing renewable energy.

Keywords: Trade, Biofuel, Environment, Globalization, Capital Flows, Technical Changes, Household Production

JEL Code: D1, F1, Q4

*The research leading to this paper was funded by the Energy Biosciences Institute and the USDA Economic Research Service under Cooperative Agreement No.58-6000-6-0051.

† *corresponding author:* 207 Giannini Hall — Berkeley, CA 94720-3310 — email: galh@berkeley.edu — Tel: (510) 642-5440 — Fax: (510) 643-8911

‡email: ssexton@are.berkeley.edu

§Member of the Giannini Foundation, Giannini Foundation — email: zilber@are.berkeley.edu

1 Introduction

Whereas non-renewable, non-recyclable petroleum was a primary source of transportation fuel around the world for most of the 20^{th} century, a number of economic and social trends seem to suggest increased reliance on renewable fuels in the 21^{st} century. These changes are driven by increasingly costly oil, heightened concern about the environment and climate change, and rising demand for energy, principally in rapidly growing Asian countries integrated to the global trade system.[1] Although during 2008 the credit crisis hampered growth in energy demand, many predict that demand will rebound once the crisis subsides (e.g., the International Energy Agency and the Energy Information Administration). The new paradigms will be characterized by the emergence of relatively clean and renewable (bioenergy) alternatives that will affect energy and food prices and patterns of trade.[2] In this paper, we extend traditional trade models and present a prototype general equilibrium framework that, different from the existing trade literature, incorporates household production (Lancaster 1966; Becker 1965), introduces energy as a ubiquitous factor in production, and defines utility over an untraded convenience characteristic and an environmental commodity to appropriately model the consequences of the introduction of biofuel crops to an energy market dominated by fossil fuel.

We assume consumers derive utility from food, the environment, and a characteristic called convenience, which is produced within the household in a production function that combines manufactured goods and energy.[3] Because households are responsible for a significant share of energy demand,[4] we incorporate household production into a general equilibrium trade model to determine the effects of trade, capital flows, technical change, and environmental and climate policy on food production, manufacturing, energy production, and environmental preservation. The environment offers local benefits in the form of open space and recreational opportunities. It also offers global benefits in the form of existence and option values associated with biodiversity. It is a public good with both local and global benefits, and decreasing in greenhouse gas emissions, a global public bad.

[1] China and India account for 51 percent of the incremental increase in demand for primary energy from 2006 to 2030 (World Energy Outlook 2008).

[2] Although bioenergy is considered by many as a promising alternative to fossil fuel, at the end of the day the efficient technology used to replace fossil fuel may include other alternative renewable technologies, such as compressed natural gas and electricity (hybrid cars), not bioenergy. Having said that, more than 77 percent of consumption of total and alternative replacement fuels in the United States during 2006 was ethanol in gasohol, i.e., low ethanol blends.

[3] This work extends Becker's work by considering energy, instead of time, as an input needed to make the final good at the household level. It is more closely related to Lancaster (1965) because it abstracts from the leisure-work trade-off. Energy is introduced as a homogeneous good affecting all stages of production and consumption.

[4] A conservative estimate attributes 22 percent of all U.S. energy consumption to households and 32 percent of all U.S. (and 8 percent of all world) carbon emissions to individuals. The amount of energy consumed by autos, motorcycles and total energy use for transportation data are taken from Table 2.7 "Highway Transportation Energy Consumption by Mode" (Transportation Energy Data Book 2007). The numbers are used to compute the fraction of total transportation energy consumed by residential users (approximately 55 percent). Total residential energy consumption is determined by summing residential sector consumption and 55 percent of transportation sector consumption according to Table 2.1a Energy Consumption by Sector: 1949-2006 (Annual Energy Review 2006, Energy Information Administration). Data were taken for the year 2001. Calculation of the fraction of residential transportation energy consumption excluded light vehicles, which include light trucks, SUVs and minivans. Therefore, this estimate is believed to provide a lower bound on the fraction of total energy consumed by households. See also Vandenbergh and Steinemann (2007).

We employ the Hecksher-Ohlin model as a clear and simple way to introduce household production in a general equilibrium trade framework and, therefore, explicitly introduce the household model to the trade literature. We assume a two-country model, with identical constant returns-to-scale production technologies and identical homothetic preferences. Both countries are endowed with labor, land, and capital. Land is used for environmental preservation and can be converted to production at a cost. Energy can be produced using either capital and labor or land and labor, using fossil fuel or biofuel technology, respectively. To produce agricultural and capital products, labor, land, capital, and energy are needed.[5] Both countries may use land taxes and emissions taxes to internalize externalities related to land conversion and energy consumption, respectively.

With this framework, we show that globalization, capital inflows, and technical changes in the manufacturing sector increase energy demand and, therefore, reduce land available for food production and the environment and increase greenhouse gas emissions. The conceptual framework suggests a trade-off between biofuel and the environment (Searchinger et al. 2008; Fargione et al. 2008), as well as a trade-off between energy and food. We also illustrate the benefits of energy-efficient goods, which reduce pressure on energy demand that result from increased capital. According to the International Energy Agency, vehicle fuel-efficiency improvements (as well as increasing oil prices) are the main drivers in mitigating world oil demand by 2030 (World Energy Outlook 2008). Furthermore, primary energy demand per unit of GDP is expected to decline by 1.7 percent per year from 2006 to 2030, as a result of rapid efficiency improvements in the power and end-use sectors in OECD countries (and also because of accelerated transitions to service economy in many non-OECD countries).

Technical changes in agriculture and in biofuel production that improve feedstock yields and conversion efficiency are shown to lessen the land constraint and thereby reduce losses of natural land and upward pressure on food prices. Emphasizing greenhouse gas reduction, while ignoring land-use changes, may lead to suboptimal outcomes. Environmental policy instruments, together with local public good characteristics of the environment, imply that factor price equalization theory does not hold because the optimal land tax is different across countries.

The economic structure of this model is described in section 2. The socially optimal equilibrium and the pattern of trade are derived in section 3, which also considers changes in capital flows. sections 4 considers changes in technology. section 5 models the effects of suboptimal policy, while section 6 discusses results and concludes.

[5]The economic structure builds on work originated by Samuelson (1953), and extended by Melvin (1968), Drabicki and Takayama (1979), Dixit and Norman (1980), Deardorff (1980), Dixit and Woodland (1982), and many others. This literature attempts to apply the law of comparative advantage to more than two goods and more than two factors. It generalizes the results of two-by-two theory to many-goods many-factors models by making the same general assumptions as in the standard two-by-two theory and looking for weaker results (see, for instance, Jones and Scheinkman 1977, Dixit and Norman 1980, and Deardorff 1982). It investigates the accuracy of the classical trade theorems: the Rybczynski theorem, the Stolper-Samuelson theorem, the Heckscher-Ohlin theorem, and the factor price equalization theorem.

2 The Economic Structure

The economic structure merges a general equilibrium trade model with a household model. It introduces a ubiquitous factor, energy, which is needed at all stages of production. Specifically, we assume a world comprised of Home and Foreign countries (denoted, respectively, by no superscript and by an asterisk), three factors, and four (intermediate) goods, in which (i) all markets are competitive, (ii) free trade prevails, and (iii) there are no transaction costs. One of the goods, convenience, is assumed to be produced at the household level. In setting the economic structure, first preferences, and subsequently consumer utility, are defined. Then, assumptions on technology are made and production is modeled.

2.1 Preferences

Assume consumers' preferences are identical across countries and are homothetic. Thus, we focus on consumers in H with consumers in F similarly defined.

Following Becker (1965) and Lancaster (1966), utility is derived from final products produced at the household level (referred to by Becker as commodities and Lancaster as characteristics). The utility function is additive, where the commodities are convenience, c, the environment, n, and food, x.[6] As in Becker, commodities are concrete and physical. However, we assume activity combines energy and manufactured goods and transforms them into convenience. Formally, convenience characteristics supply the household with basic needs, satisfaction, and fun and are produced from manufactured products, y (e.g., car, computers, or homes), and energy E_c, where $g_c(y, E_c)$ denotes the *activity* that combines manufactured goods and energy and *transforms* them into convenience, i.e., $c = g_c(y, E_c)$ (a la Lancaster 1965). We assume that $g_c(y, E_c)$ is increasing and concave in its arguments, and is homogeneous of degree one.

The environmental commodity, which increases in natural land A_n and decreases in emissions of greenhouse gases Z, is denoted by $n \equiv g_n(A_n, Z)$. This function is assumed to be concave, where $\partial g_n/\partial A_n > 0$, $\partial^2 g_n/\partial A_n^2 \leq 0$, and $\partial g_n/\partial Z < 0$, $\partial^2 g_n/\partial Z^2 \leq 0$. For the sake of simplicity, we assume the food commodity equals purchased food products x.

2.1.1 Consumers

Consumers maximize an additive utility function

[6] Note that land for environment has use benefits (including, recreation, environmental services, etc.) and non-use benefits (including biodiversity, option value, bequest value, etc.).

$$U = u_x(x) + u_y(c) + u_n(n). \tag{1}$$

Subutility $u_x(x)$ is concave, i.e., $\partial u_x/\partial x > 0$ and $\partial^2 u_x/\partial x^2 \leq 0$, and so are $u_c(c)$ and $u_n(n)$. Note that these assumptions imply that all goods are normal goods.[7]

The prices of x, y, and E, are, respectively, p_x, p_y, and p_E, where without loss of generality, we normalize the price of manufactured goods to 1 (and, henceforth, let $p \equiv \frac{p_x}{p_y}$). Consumers take disposable income I as given. Hence, the budget constraint can be written as

$$p_x \cdot x + p_c \cdot c \leq I, \tag{2}$$

where $p_c \equiv a_{y_c} + a_{E_c} \cdot p_E$ and where a_{j_i} denotes the cost-minimizing amount of factor j used to produce one unit of good i. Consumers solve the household problem in two steps. First, given factor prices, they choose the bundle of factors that minimize the cost of producing a given amount of convenience. Then they maximize their utility subject to their budget constraint.[8]

2.2 Technology

Labor, L, land, A, and capital, K, are used to produce energy using two alternative technologies:

$$E^f = g_E^f\left(L_E^f, K_E^f\right) \text{ and } E^b = g_E^b\left(L_E^b, A_E^b\right). \tag{3}$$

Superscripts f and b denote fossil fuel and biofuel, respectively. We think the transition to a long-run equilibrium with no fossil fuel is more important than the long-run equilibrium itself. Therefore, we do not introduce a finite capacity for fossil fuel. To this end, recent empirical papers found little evidence for non-myopic behavior among oil-extracting countries/companies during the 20^{th} century (Hamilton, 2008). Having said that, the reader may assume that the marginal cost of extracting energy from fossil fuel includes user costs and, therefore, incorporates the dynamic characteristics of extracting a non-renewable resource.

Let $A_E \equiv A_E^b$, $K_E \equiv K_E^f$, $L_E \equiv L_E^f + L_E^b$, and $E \equiv E^f + E^b$. Fossil fuel is produced using labor and capital, whereas biofuel is produced using labor and land. Capital is needed to drill and pump oil, whereas land is needed to grow biomass to produce biofuel.[9]

[7] To derive the main results of the paper it is sufficient to assume homothetic preferences. Assuming additive separability allows us to abstract from cross-derivatives and, therefore, simplifies the presentation.

[8] Assuming an additive utility function implies that the conditions required for two-step maximization hold (see Green 1964).

[9] Although the production of energy from biofuel crops uses capital, it is less capital intensive than extraction of energy from fossil fuel. Moreover, introducing capital to production of energy from biofuel crops, and assuming energy from fossil fuel is more capital intensive, will not add much to the discussion. Therefore it is omitted.

To understand the fundamental economics behind biofuels, our analysis assumes competitive energy and agricultural markets and abstracts away from agricultural policies and subsidies that are addressed elsewhere in the literature (Gardner and Tyner 2007; de Gorter and Just 2008; among others).[10] We depict the demand D and supply S of energy in Figure 1 given the price of food p, where the "kink" in the supply function stems from the assumption that at low prices, i.e., energy prices below p_0, it is profitable to produce energy using fossil fuel, but it is not profitable to produce it using biofuel. An increase in the price of food increases the break-even price p_0.[11]

Figure 1: The Energy Market

Food is produced using labor, L_x, capital K_x, land A_x, and energy E_x. Manufactured goods are produced with similarly defined inputs. Hence, the production functions are, respectively,

$$x = g_x\left(L_x, K_x, A_x, E_x\right) \quad \text{and } y = g_y\left(L_y, K_y, A_y, E_y\right). \tag{4}$$

The production functions are increasing, concave in inputs, and homogenous of degree one.

The aggregate quantities of labor, capital, and land are given, respectively, as $\overline{L}$, $\overline{K}$, and $\overline{A}$. Therefore, the economy's resource constraints are

$$\begin{aligned} \overline{K} &= K_E + K_x + K_y \\ \overline{L} &= L_E + L_x + L_y, \text{ and} \\ \overline{K} &= A_E + A_x + A_y + A_n \end{aligned} \tag{5}$$

Assume also that E, x, and y, are traded goods.

The combustion of fossil fuel produces carbon emissions, as does conversion of biofuel crops to energy. Reallocating land to production releases the carbon captured in natural biomass and soil and produces carbon emissions (Sedjo et al. 1995; Plantinga and Wu 2003). We, therefore, assume the "emissions function" is $Z \equiv g_Z\left(E_p, A_p\right)$, such that $\partial g_Z/\partial E_p > 0, \partial g_Z/\partial A_p > 0$ and $\partial^2 g_Z/\partial E_p^2 > 0$, $\partial^2 g_Z/\partial A_p^2 > 0$, where $E_p \equiv E^f + E^{*f} + \rho\left(E^b + E^{*b}\right)$ and $A_p \equiv \overline{A} - A_n + \overline{A}^* - A_n^*$.

[10] With gasoline prices reaching nominal highs at retail stations and even real records not seen since the 1970's oil crisis, and with oil trading at beyond 100 USD per barrel (the International Energy Agency predicts that the average price of oil in real terms, using 2007 as the base year, will be 100 USD for the period 2006 to 2030), not only efficient biofuel crops such as sugarcane to ethanol are cost competitive with gasoline but also corn ethanol; at 100 USD a barrel many biofuel crops are efficient without government support. An exploration of the economics, policy, and history of biofuel in the United States can be found in de Gorter and Just (2008), Gardner (2007), among others.

[11] To this end, Tyner and Taheripour (2007) used U.S. data from 2007 to determine the cost of gasoline at which the typical corn-ethanol plant can break even (earn zero economic profits) for any price of corn. They found that, with oil trading at 72 USD per barrel (as it did in 2007, according to the U.S. Energy Information Administration), ethanol plants could earn positive profits for corn prices below 4 USD with a 0.51 USD subsidy and below roughly 2.75 USD without the subsidy.

Much of the analysis on biofuel and greenhouse gases emits less greenhouse gases than gasoline. Thus, without loss of generality, we assume $\rho < 1$.[12]

To simplify the exposition, and without loss of generality, we assume that H is capital abundant and F is labor abundant, and that country endowments are sufficiently similar.

Assumption 1 $\frac{\bar{K}}{K^*} > \frac{\bar{A}}{A^*} > \frac{\bar{L}}{L^*}$.

Assumption 1 states that the amount of capital per worker (land) in country H is larger than the amount of capital to labor (land) in country F.

2.2.1 Producers

Using the production function of sector $q \in \{x, y\}$, while applying the dual approach to trade theory (see Dixit and Norman, 1980; Bhagwati et al., 1998; among others), the minimum per-unit cost of production of a good as a function of factor prices is

$$c_q(w, s, r, p_E) = \min_{\{a_{Lq}, a_{Aq}, a_{Kq}, a_{Eq}\}} \{w \cdot a_{Lq} + s \cdot a_{Aq} + r \cdot a_{Kq} + p_E \cdot a_{Eq} : g_q(a_{Lq}, a_{Aq}, a_{Kq}, a_{Eq}) \geq 1\}, \tag{6}$$

where unit cost of labor, capital, and land, are w, r, and s, respectively. The values $\{a_{Lq}, a_{Aq}, a_{Kq}, a_{Eq}\}$ that solve the problem are the cost-minimizing input-output coefficients. Since the unit cost function is concave, its Hessian matrix is negatively semi-definite and has non-positive diagonal elements; thus,

$$\frac{\partial a_{Lq}}{\partial w} \leq 0, \frac{\partial a_{Aq}}{\partial s} \leq 0, \frac{\partial a_{Kq}}{\partial r} \leq 0, \text{ and } \frac{\partial a_{Eq}}{\partial p_E} \leq 0. \tag{7}$$

The economic intuition is that as a factor becomes relatively more expensive, cost-minimizing firms tend to substitute it with a cheaper factor. This implies that firms in sector q jointly maximize the sector's profits by choosing the appropriate inputs.

2.2.2 The policy instruments

Biofuel crop production and fossil fuel consumption introduce externalities. Land reallocated for production is costly because it reduces land allocated to the environment, a public good with local

[12] Clearly, sugarcane ethanol emits less greenhouse gases than gasoline, whereas corn ethanol may decrease or increase greenhouse gas emissions relative to gasoline (Farrell et al., 2006; Rajagopal and Zilberman 2008; among others). But even the dirtiest corn ethanol emits less greenhouse gas emissions than gasoline produced from tar sand (Rajagopal et al. 2008).

and global benefit. Consumption of fossil fuel causes carbon emissions, a global public bad. We assume that governments intervene in markets to internalize the environmental externalities and achieve policies that results in efficient outcomes that represent globally optimal resource allocations. This outcome occurs when the generators of carbon greenhouse gasses emissions as well as those diverters of land to production pay the social cost of their activity. Since greenhouse gas emissions are a global public bad, their damage is spread globally and not contained in one country; globally efficient outcomes occur when polluters pay a carbon tax that equals the sum of the marginal damage from carbon emissions to people across the world. Correcting the environmental impact of land conversion to agricultural or biofuel production, requires a tax payment that is equal to the marginal cost of the greenhouse gases emitted by the land conversion plus the marginal cost from loss of open spaces. So, for example, if planting sugarcane for biofuel results in deforestation, then the resulted greenhouse gas emissions should be paid.[13]

Formally, we assume two-policy instruments are used to internalize the externalities: a land tax and a carbon tax. The land tax can alternatively be considered a land conversion permit fee. The same incentive can be provided by payment (subsidies) for environmental services provided by land (Zilberman et al. 2008). The carbon tax can be implemented through a gasoline tax and a biofuel subsidy that accounts for the emissions difference between fossil fuel and biofuel (see also Fullerton and West 2002). Let $\Psi > 0$ and $\Phi > 0$ denote the land tax and carbon tax, respectively.

3 The Social Optimum Trade Equilibrium

We analyze the extended trade model, given a non-traded good produced at the household level. We investigate the four standard trade theorems: the Stolper-Samuelson theorem, the Rybczynski theorem, the Heckscher-Ohlin theorem, and the factor price equalization theorem. We accomplish this in two steps: First, assuming land is allocated to maximize firm profits, we can rewrite the production functions of x and y as functions of capital, land, energy, and real land tax only.[14] We apply these techniques, given that land can be used either for production or for environment. Second, and after reducing the dimensionality of our problem, we derive equilibrium prices and resource allocations. The equilibrium prices and resources allocations are first derived for a small open economy. Then, the analysis is extended to a big economy.

3.1 The Trade Equilibrium: A small open economy

Appendix A presents a modified version of the Stolper-Samuelsom theorem (Samuelson 1953) to our expanded framework. Specifically, and different from the standard trade models, prices of factors

[13] Although the outcome of a carbon tax can be achieved with a system of carbon-trading permits (Atkinson and Tietenberg 1991), for simplicity our analysis is presented in terms of carbon tax.

[14] These techniques were also used to examine the validity of the four fundamental trade theorems in the presence of international capital movement (e.g., Leamer 1984, Ethier and Svensson 1986, and Wong 1995).

and of non-traded goods are determined uniquely not only by the international prices of traded goods, but also by the policy instruments – the carbon and the land taxes.[15]

Let $s_q = \frac{s}{p_q}$ be the real rent of land in terms of good q, and define

$$G_q\left(L_q, K_q, E_q, s_q\right) \equiv \max_{A_q}\left\{p_q \cdot g_q\left(L_q, A_q, K_q, E_q\right) - s_q \cdot A_q\right\}.$$

The function $G_q\left(L_q, K_q, E_q, s_q\right)$ behaves like a production function (see Appendix A, Section 7.1.1). To derive the equilibrium, note that the production functions are homogenous of degree one and, therefore,

$$G_q\left(K_q, L_q, E_q, s_q\right) = L_q \cdot G_q\left(\frac{K_q}{L_q}, 1, \frac{E_q}{L_q}, s_q\right) \equiv L_q \cdot \widetilde{G}_q\left(\ k_q, e_q, s_q\right),$$

where $k_q = \frac{K_q}{L_q}$ denotes the capital-labor ratio and $e_q = \frac{E_q}{L_q}$ denotes the energy-labor ratio.

Building on the result derived in Appendix A, while using the notation presented above, we derive a modified Heckscher-Ohlin-Vanek Theorem. Formally, let $\omega = \frac{w}{r}$, and $\upsilon \equiv \frac{w}{s}$. In addition, let MP_q^i denote the marginal productivity of input i, $i \in \{K, E, L, A\}$, in production of good q, $q \in \{x, y\}$, and assume $\lim_{i \to 0} MP_q^i = \infty$ and $\lim_{i \to \infty} MP_q^i = 0$. These are the *Inada Conditions.*

Lemma 1 *Given the Inada Conditions, the relative price of food p, the land tax Ψ, and the carbon tax Φ determine uniquely s, ω, and υ. They also uniquely determine the capital-labor and the energy-labor ratio in sectors E, x, and y, as well as the allocation of land between the different sectors.*

Proof: Follows from Lemma 1A in Appendix A, given the resource constraint, i.e., equation (2), and the zero-profit condition. See Appendix A.

The government sets the land tax equal to the marginal benefit from open spaces (a local public good), i.e., $\Psi = \frac{\partial u_n}{\partial n} \cdot \frac{\partial g_n}{\partial A_n}$, which does not include emissions from reallocating land to production, i.e., $\frac{\partial g_Z}{\partial A_n}$. The government also sets a carbon tax equal to the global marginal cost of emissions, i.e., $\Phi = -\left(\frac{\partial u_n^*}{\partial n^*} \cdot \frac{\partial g_n^*}{\partial Z} + \frac{\partial u_n}{\partial n} \cdot \frac{\partial g_n}{\partial Z}\right)$. For each unit of carbon produced by combustion of fossil fuel and biofuel, users pay. In addition, emissions from converting natural land to production are taxed, i.e., tax on emissions from land-use change equals $\Phi \cdot \frac{\partial g_Z}{\partial A_n}$. Similar to the Heckscher-Ohlin trade model, factor prices determine the input-output coefficients. Different from these models, the cost of land is determined by the government.

[15] The paper, therefore, also extends the work of Komiya (1967) who showed that if the number of internationally-traded goods is equal to or greater than the number of production factors among countries, then factor prices and commodity prices are equalized.

Lemma 2 *The price of land increases in emissions and in land reallocated to production, i.e.,* $s = \Psi + \Phi \cdot \frac{\partial g_Z}{\partial A_n}$ *(recall that* $\Phi > 0$*).*

In equilibrium, and because all markets are competitive,

$$p \cdot MP_E^x = p_E = MP_E^y \text{ and } p \cdot MP_A^x = s = MP_A^y, \tag{8}$$

where the price of energy p_E equals the marginal cost of producing energy using fossil fuel plus the marginal cost of pollution from extraction and combustion of fossil fuel, i.e., $\Phi \cdot \frac{\partial g_Z}{\partial E}$, which in turn equals the marginal cost of producing energy using biofuel plus the marginal cost of emissions from production of biofuel crops, i.e., $\rho \cdot \Phi \cdot \frac{\partial g_Z}{\partial E}$.

A fuel tax, unlike a carbon tax, is easier to implement, and its level may vary with the energy content of the various fuels. Here, the optimal fuel taxes equal the marginal cost of carbon emissions associated with consumption of fossil fuel and ethanol, i.e., $\Phi \cdot \frac{\partial g_Z}{\partial E}$ and $\rho \cdot \Phi \cdot \frac{\partial g_Z}{\partial E}$, respectively. An alternative land tax, which yields the same efficient allocation of resources between production and the environment, is to assume that land is initially allocated to production, and the government pays landowners not to use their land. By paying s for environmental services, the regulator internalizes the externality associated with land conversion and increases environmental preservation. A regulator may also apply zoning laws or issue permits for land conversion, although allocating A_n units of land to the environment or allocating permits to utilize $\bar{A} - A_n$ units of land has different implications for distribution of total surplus (see Cropper and Oates 1992).

3.1.1 Capital Accumulation

This section investigates how an increase in capital affects the free trade equilibrium. Borrowing the terminology of Jones and Scheinkman (1977), we show that capital is a "friend" to manufactured goods and an "enemy" to food. This is the familiar Rybczynski effect, which in our case implies that an increase in capital boosts the amount of manufactured goods produced and reduces the amount of food produced. This result is shown while exploiting the full-employment conditions (equation (6)). Increasing $\overline{K}$ not only changes the pattern of production (as predicted by the Rybczynski effect), but also increases the amount of land allocated to production.

Proposition 1 *Increasing capital* $\overline{K}$ *increases the amount of land allocated to producing the manufactured goods, while reducing land allocated to the environment, and raises the level of emissions* Z*.*

Proof: The proof is relegated to Appendix B.

Let $\Delta K/\bar{K}$ denote the proportional change in capital. The increase in capital causes the marginal benefit from land to increase, hence demand for land shifts up and to the right; land-use change emissions from biofuel production increases. Therefore, the increase in capital ΔK should be supplemented by an increase in land ΔA and an increase in land and carbon taxes. Furthermore, increased production raises demand for energy, which also raises emissions. Figure 2 summarizes this result, where S denotes the supply of land for production and the inverse demand for land is $D^{-1}(.)$. If $\bar{K}_0 < \bar{K}_1$, then $A_{n,0} \geq A_{n,1}$ $(A_{p,0} \leq A_{p,1})$, and therefore $s_0 < s_1$. Moreover, the higher is the supply elasticity of land allocated to production, the bigger is the reallocation of land to production induced by capital inflows (and the higher is the level of emissions in the economy). This conclusion is consistent with empirical observation that shows an increase in foreign direct investment relative to domestic capital investment in countries like China and India and is accompanied by an increase in energy demand and a subsequent increase in the quantity of manufactured goods supplied (World Investment Report, 2000).

Figure 2: Demand for Land for Production

3.2 The Trade Equilibrium: A Large Open Economy

We now show that although trade may equalize the price of the traded goods, this condition is not sufficient for factor price equalization. Differences in land endowments across countries, a homogenous input in our model, imply differences in the marginal benefit from natural land across countries. Differences in marginal benefit from land suggest differences in land and emission taxes.

To determine how a change in p changes the carbon tax, assume an increase in land to the environment permits greater carbon sequestration and, therefore, reduces the cost of carbon emissions, $\frac{\partial \Phi}{\partial A_n} < 0$. Then, it can be shown that

$$\frac{d\Phi}{dp} = \frac{\partial \Phi}{\partial A_n}\frac{dA_n}{dp} + \frac{\partial \Phi}{\partial Z}\frac{dZ}{dp} > 0$$

An increase in p increases the food sector's demand for land, yielding less land for the environment and for biofuel, i.e., $\frac{\partial A_n}{\partial p} < 0$. The decline in energy supplied using biofuel will trigger an increase in the supply of fossil fuel, which increases carbon emissions, i.e., $\frac{\partial Z}{\partial p} > 0$, and the marginal cost of emissions, $\frac{\partial \Phi}{\partial Z} > 0$. Similarly, it can also be shown that

$$\frac{d\Psi}{dp} = \frac{\partial \Psi}{\partial A_n}\frac{dA_n}{dp} + \frac{\partial \Psi}{\partial Z}\frac{dZ}{dp} > 0.$$

Lemma 3 *The land tax and carbon tax are an increasing function of p, i.e.,* $\frac{d\Psi}{dp} > 0$ *and* $\frac{d\Phi}{dp} > 0$.

Lemma 2, together with Lemma 1, generalizes the Stolper-Samuelson theorem:

Proposition 2 *Assume the Inada Conditions. The relative price of food, p, and the endowments determine ω and υ. They also determine the capital-labor and energy-labor ratios in sectors E, x, and y, as well as the allocation of land between the different sectors.*

Prices of traded goods do not uniquely determine factor prices; factor prices also depend on the endowments, which affect the environmental policies.

3.3 The Pattern of Trade

Rather than focusing on specific commodities, this paper derives the (indirect) trade flow of factor content, following the classic work of Vanek 1968.[16]

Proposition 3 *(Heckscher-Ohlin-Vanek Theorem) Given Assumption 1, if both the carbon tax and the price of land are the same across countries, i.e., $\Phi = \Phi^*$ and $s = s^*$, then H exports capital and imports labor. If, on the other hand, the price of land in country H is higher than in country F, i.e., $s > s^*$, then F exports land.*

Proof: The proof is relegated to Appendix B.

From Proposition 3 we conclude that a country exports the service of the factor in which it is most abundant.[17] We cannot conclude, however, which goods H (or F) exports. This is also true if, instead of three factors, we had only two factors of production, as shown by Bhagwati (1972).[18] Different from the standard Heckscher-Ohlin model, equalizing commodity prices does not imply factor price equalization. The reason is that policy instruments, i.e., the carbon tax and the land tax, affect producer profits and are a function of countries' endowments. It is socially optimal for the land-abundant country to have lower land taxes.

Next, we derive world demand and world supply of energy, and then evaluate how changes in relative prices affect them. The amount of energy supplied by each country can be computed using Hotelling's Lemma (firms maximize profits and are assumed to be price takers) when energy is produced using both biofuel and fossil fuel. The demand for energy, on the other hand, can be computed using Shephard's Lemma because goods x and y are produced by profit-maximizing firms

[16] Vanek (1968) was extended by Horiba (1974), Leamer (1980), Brecher and Choudhri (1982), Deardorff (1982), Ethier (1984), Helpman (1984), Deardorff and Staiger (1988), Trefler (1993), Davis, Weinstein, Bradford and Shimpo (1997), and Davis and Weinstein (1996), among many others.

[17] To this end, Proposition 3 follows from Brecher and Choudhri (1982) and Helpman (1984), which show that, on average, a country exports services of the factors that are cheaper under free trade. If the policy instruments are equalized in equilibrium and given Assumption 1, F exports labor services to H and imports capital from H. Proposition 3, therefore, draws from Staiger (1986), which shows that, on average, if factor prices are equalized, then a country exports services of the abundant factor.

[18] The chain version of the Heckscher-Ohlin theorem was first proposed by Jones (1956-1957). Deardorff (1979) provides a formal proof of the theorem in the absence of factor price equalization under free trade. Deardorff also shows that the theorem remains valid in the presence of tariffs or intermediate goods, but not both.

(cost minimizing). Similar techniques can also be used to compute the amount of energy demanded at the household level. Households are price takers, and their maximization problem is solved in two steps: (i) minimize the unit cost of producing commodity c, and (ii) derive the optimal amount consumed of c.

Proposition 4 *Given prices of traded goods, i.e., p and p^*, world demand for energy increases when countries open to trade.*

Numerous studies have shown, given homothetic preferences, profit-maximizing firms, and convex technology, that GDP increases with trade.[19] Trade increases the consumption possibilities frontier and allows countries to produce more efficiently. Therefore, the amount spent on each (intermediate) good, including energy, increases with trade. For given prices, liberalizing trade causes the demand for energy, and therefore greenhouse gas emissions, to increase.

Because energy is produced more efficiently under trade (trade introduces an efficient, albeit indirect, method of production), world supply of energy increases. Furthermore,

1. If energy and capital are complements at the household level, $\frac{\partial^2 g_c}{\partial y_c \partial E_c} > 0$, and $u(c) = c$, then household (residential) demand for energy increases, and
2. If energy and capital are complements at the production level, $\frac{\partial^2 g_q}{\partial K_q \partial E_q} > 0$ for $q \in \{x, y\}$, then industry demand for energy in F increases.

The assumption that capital and energy are complements is consistent with Pindyck and Rotemberg's (1983) findings, and is plausible when both capital and the manufactured good are assumed to be homogeneous.

4 The Environment

The definition of sustainability supplied in the Bruntland Report (1987) suggests that biofuel should meet the needs of the present without compromising the ability of future generations to meet their own needs (see also Khana et al. 2009). Biofuel should promote economic and social development, while avoiding environmental degradation, over-exploitation, or pollution. For these reasons, and although we assumed governments strive to achieve the social optimum, we elected to explicitly focus on the environment and, after characterizing the social optimum solution, illustrate how suboptimal policy may bias the solution away from the social optimum. To this end, the environment indifference curve $u_n(n) = \bar{u}_n$ is characterized next.

[19] As shown by Samuelson (1939 and 1962), Kemp (1962), Bhagwati (1968), Grandmont and McFadden (1972), Kemp and Wan (1972), Ohyama (1972), and Kemp and Ohyama (1978), among others.

Lemma 4 *The environment indifferent curve is upward sloping in the energy-natural land plane; that is,*

$$\frac{dE_p}{dA_n} = -\left(\frac{\partial g_n}{\partial A_n} + \frac{\partial g_n}{\partial Z} \cdot \frac{\partial Z}{\partial A_n}\right) / \left(\frac{\partial g_n}{\partial Z} \cdot \frac{\partial Z}{\partial E_p}\right) > 0.$$

Lemma 4 tells us that the environment indifference curves slope downward in the $A_p - E$ plane. In Figure 3 we depict two generic environment indifference curves, where $u_n^0 > u_n^1$. It is easy to verify that the benefit from the environment increases if we move down and to the left in the A_p and E plane. An increase in the relative price of food x increases the amount of land allocated to food production, partly at the expense of the environment, $\partial A_n/\partial p < 0$, and partly at the expense of biofuel. The reduction in energy production using biofuel crops increases demand for energy extracted from fossil fuel, which increases the quantity supplied E^f, i.e., $\partial E^f/\partial p > 0$. The increase in the price of food, however, also reduces land-use change emissions from biofuel production, and also increases production in the land-intensive food sector, and thus reduces production in the energy-intensive manufacturing sector (energy demand goes down).

Figure 3: The Environment Indifferent Curve

If land-use change emissions from reallocating land to production are small, i.e., $\partial g_Z/\partial A_n$ is small, a carbon tax induces substitution of biofuel for fossil fuel, whereas a land tax makes biofuel production more costly. A carbon tax, therefore, accomplishes two related aims: the reduction of fossil fuel emissions and the development of biofuels. A land tax, on the other hand, can increase open space and preserve wildlife. A land tax has the opposite effect of a carbon tax on land allocations by reducing biofuel production.[20]

Proposition 5 *Assume the land-use change emissions are sufficiently small, i.e., $\partial g_Z/\partial A_n$ is not too large. A carbon tax (land tax) increases (decreases) the ratio of energy produced from biofuel to energy extracted from fossil fuel, i.e., E^b/E^f.*

Proposition 5 highlights an important drawback of a carbon tax: Although a carbon tax reduces greenhouse gases from fossil fuel, it does so at the expense of biodiversity and food production. Because a carbon tax leads to substitution of biofuel for fossil fuel, it increases the competition for scarce land resources among food production, the environment and biofuel. In a dynamic setting, this increase in competition may lead the energy market to seek alternative, and cleaner, ways of extracting energy (e.g., natural gas and renewable resources). The land tax, on the other hand, reduces deforestation and protects biodiversity, but shifts the energy portfolio toward greater reliance of fossil fuels, which produces greater greenhouse gas emissions.

[20]Note that if emissions related to the inputs used in production of biofuel increase greenhouse gas emissions relative to its fossil substitute (e.g., the use of coal to convert corn to ethanol, as opposed to natural gas), the logic is reversed; a carbon tax decreases the ratio E^b/E^f. Furthermore,

The analysis presented above suggests policy should include both a carbon tax and a natural land tax. The carbon tax maybe implemented as a fuel tax that differentiates between different fuels based on their carbon footprint, and a land conversion tax that assigns a monetary value to release of stored carbon. Whereas the land tax should internalize the cost from land-use changes; changes causing biodiversity loss and reduction of natural land. These policy recommendations pose a challenge, because partial policy (e.g., pursuing policy to reduce green house gases, while ignoring biodiversity loss) may create significant loss of welfare, and in principle may even become counter productive. Although the determination of the socially optimal solution includes the externality costs in the calculation, governments might set taxes sub-optimaly low due to political economy reasons or failure to correctly determine externality costs. Politics, for example, might cause the regulatory agency to undervalue the environment and overvalue producers. Needless to say that these argument depend on strategic considerations, not formally modeled in the paper, because in the absence of such consideration, an economy is necessary better-off with more instruments provided the government can choose their level.

Sub-optimal land tax. A sub-optimal regime which neglects the land tax creates incentives for countries like Brazil to over-utilize their rain forests, which not only increases land-use change emissions but also reduces biodiversity. We illustrate this in the current section. To this end, assume a country sets the land tax sub-optimally, i.e., $\Psi < \Psi^0$, where superscript 0 denotes the social optimal solution. All else being equal, and because land is cheaper to use, the amount of land allocated to production increases, i.e., $\bar{A} - A_n$ increases. Then, the Rybczynski effect implies that the land intensive industry expands whereas the other sector contracts; in other words, x increases and y decreases. The change in allocation of land also affects the emissions tax. By totally differentiating the emissions tax Φ with respect to A_n, we see:

$$\begin{aligned}\frac{d\Phi}{dA_n} = - \quad & \frac{\partial^2 u_n}{\partial n^2}\left(\frac{\partial g_n}{\partial A_n} + \frac{\partial g_n}{\partial Z}\frac{\partial Z}{\partial A_n}\right)\frac{\partial g_n}{\partial Z} - \frac{\partial u_n}{\partial n}\left(\frac{\partial^2 g_n}{\partial A_n \partial Z} + \frac{\partial^2 g_n}{\partial Z^2}\frac{\partial Z}{\partial A_n}\right) \\ - \quad & \frac{\partial^2 u_n^*}{\partial {n^*}^2}\left(\frac{\partial g_n^*}{\partial Z}\right)^2 \frac{\partial Z}{\partial A_n} - \frac{\partial u_n^*}{\partial n^*}\frac{\partial^2 g_n^*}{\partial Z^2}\frac{\partial Z}{\partial A_n}\end{aligned}$$

Proposition 6 *If natural land mitigates the cost of emissions, i.e.,* $\frac{\partial^2 g_n}{\partial A_n \partial Z} > 0$*, and the marginal cost of emissions increases with total emissions, i.e.,* $\frac{\partial^2 g_n}{\partial Z^2} < 0$ *and* $\frac{\partial^2 g_n^*}{\partial Z^2} < 0$*, then the emissions tax decreases with natural land* $\frac{d\Phi}{dA_n} < 0$*.*

Lower than optimum land taxes reduce natural land, and therefore decreases the stock of land allocated to nature. To compensate for the reduction in natural land, the level of emissions is reduced further because a higher carbon tax is now levied. This is true if $\frac{\partial^2 g_n}{\partial A_n \partial Z} > 0$, $\frac{\partial^2 g_n}{\partial Z^2} < 0$, and

$\frac{\partial^2 g_n^*}{\partial Z^2} < 0$.[21] In other words, if the utility from nature is sufficiently concave, i.e., the curvature of $u_n(.)$ $\left|\frac{\partial^2 u_n}{\partial n^2}\right| / \frac{\partial u_n}{\partial n}$, is sufficiently large, then loss in environmental benefit from lower land taxes is mitigated by lower emissions (higher emissions tax). The carbon tax substitutes, albeit not perfectly, for natural land.

Proposition 6, together with the Rybczynski effect, implies under certain conditions that emissions, Z, are lower and land allocated to the environment is lower, i.e., A_n decreases, relative to the social optimum (see Fig. 4, where point A denotes to social optimum solution and point B denotes the sub-optimal solution). Optimality implies also that $u_n^0 > u_n^1$ where superscript 0 denotes the social optimum and 1 denotes the sub-optimal solution (total utility from consumption goes-up).

Figure 4: The Environment Indifferent Curves and Comparative Static

Note that if food production is not energy intensive, resources are attracted to the manufacturing sector and food production declines. If land is undervalued, an emissions tax will trade biodiversity for emission reductions and expansion of productive land relative to the social optimum. Mooney and Hobbs (2000) contend the cost of biodiversity loss presently outweighs the cost of emissions.

Sub-optimal carbon tax. Under this alternative scenario, emissions increase and land tax is higher than its socially optimal level.

Proposition 7 *If natural land mitigates the cost of emissions, i.e.,* $\frac{\partial^2 g_n}{\partial A_n \partial Z} > 0$*, then land tax increases with emissions* $\frac{d\Psi}{dZ} = \frac{\partial^2 u_n}{\partial n^2}\frac{\partial g_n}{\partial A_n}\frac{\partial g_n}{\partial Z} + \frac{\partial u_n}{\partial n}\frac{\partial^2 g_n}{\partial A_n \partial Z} > 0$.

When carbon tax is set lower than its socially optimal level, the regulator uses land taxes to compensate the environment for the increase in emissions (assuming $\frac{\partial^2 g_n}{\partial A_n \partial Z} > 0$). A higher land tax leads to under-utilization of land, contraction of food production, and higher than optimal food prices, in contrast to the social optimum solution. Furthermore, if the greenhouse gas emissions from land conversion are sufficiently small, a higher than optimal land tax makes biofuel more expensive, when compared to their social optimum level. Resources used to extract fossil fuel are over utilized, whereas biofuel is produced at suboptimal levels.

The non-cooperative solution Throughout the paper we assumed the two countries cooperate on environmental policies to achieve the social optimum. However, in reality, not all countries join

[21] The cross derivative $\frac{\partial^2 g_n}{\partial A_n \partial Z} > 0$ implies land mitigates the cost of emission (e.g., $g_n(A_n, Z) = \ln(A_n) - \frac{z^2}{A_n}$), whereas $\frac{\partial^2 g_n}{\partial A_n \partial Z} < 0$ implies natural land is good to the environment and emissions is bad (e.g., $g_n(A_n, Z) = \ln\left(A_n/Z\right)$). Land mitigates the cost of emission when it absorbs carbon from the atmosphere, i.e., carbon sequestration.

an environmental agreement (e.g., the United States chose not to join the Kyoto protocol). To model this outcome using the current structure, assume policy is set unilaterally. Then, it is straight forward to show that if only one country levies an emission taxes, it sets them higher than its socially optimal level. Let Φ^{o} denote the social optimum emissions tax.

Proposition 8 *If only country H levies an emission tax, then the constrained optimal emission tax is larger; that is, if* $\Phi^{*}=0$ *then* $\Phi^{o}<\Phi$

Because greenhouse gases are a global public bad, the optimal solution suggests all countries should bare the cost of emissions and levy a carbon tax. When, as shown by the Kyoto protocol, some countries elect to internalize the emissions cost while others do not, Proposition 8 tells us that some countries share a larger monetary burden than implied by the social optimum solution. Intuitively, if only one country decides to internalize the global cost of emissions, the marginal cost of emitting one more unit of greenhouse gases will be larger and therefore the tax levied on emissions larger. This suggests a "leadership cost", and an incentive to include as many countries as possible in an international environment agreement.

5 Technical Changes

This section focuses on small technical changes, and how they affect prices, production and land allocation. Throughout the analysis we assume that the technical changes do not change the factor intensity of production. Section 4.1 and 4.2 focus on *neutral technical* changes, where neutral technical changes shift up the marginal product of all factors in the same proportion for all capital-labor and energy-labor ratios. Formally, the production function is of the form $\mu\tilde{G}(.)$, where μ denotes the technical-change parameter. The sections depicting the impact of technical changes on the manufacturing and the food sector (the first two sections) assume a small economy, and fixed prices. Introducing a big economy does not alter the results. The third section, which focuses on technical changes in biofuels assumes a big economy, i.e., commodity prices change, it highlights the benefit from improving energy crop yield while reducing demand for land; namely, second generation biofuel crops.

5.1 Technical changes in the manufactured good sector

We start with technical changes in the production of capital goods, i.e., $\mu_y>1$, and assume perfect competition in input markets. Then

$$p=\mu_y\cdot\frac{\partial\widetilde{G_y}(.)/\partial k_y(.)}{\partial\widetilde{G}_x(.)/\partial k_x(.)}\text{ and }p=\mu_y\cdot\frac{\partial\widetilde{G_y}(.)/\partial e_y(.)}{\partial\widetilde{G}_x(.)/\partial e_x(.)}.\tag{9}$$

Let us define the capital-labor unit coefficient ratio of capital goods and food $s_k^{yx} \equiv k_y/k_x$, the elasticity of supply of q with respect to e and k,

$$\eta_{qe} \equiv \frac{e_q}{\widetilde{G}_q(.)}\frac{\partial \widetilde{G}_q(.)}{\partial e_q} > 0 \text{ and } \eta_{qk} \equiv \frac{\partial \widetilde{G}_q(.)}{\partial k_q}\frac{k_q}{\widetilde{G}_q(.)} > 0$$

and a measurement of concavity of $q \in \{x, y\}$ with respect to k_q

$$\Delta_{k,q} \equiv -\frac{\frac{\partial \widetilde{G}_q(.)}{\partial k_q}}{\frac{\partial^2 \widetilde{G}_q(.)}{\partial k_q^2}} > 0.$$

The larger the curvature of q with respect to k, i.e., the more concave is $\widetilde{G}_q(.)$, the smaller is $\Delta_{k,q}$. Let us further define

$$\Gamma^q_{ke,e} \equiv \frac{\frac{\partial^2 \widetilde{G}_q(.)}{\partial e_q \partial k_q}}{\frac{\partial \widetilde{G}_q(.)}{\partial e_q}}$$

where $\text{sign}\left(\Gamma^q_{ke,e}\right) = \text{sign}\left(\frac{\partial^2 \widetilde{G}_q(.)}{\partial e_q \partial k_q}\right)$. The variable $\Gamma^q_{ke,e}$ measures the change in the marginal productivity of the capital-labor ratio due to a marginal increase in the energy-labor ratio; a large and positive coefficient suggest energy and capital are complements, whereas a negative coefficient suggests the two are substitutes. Similarly define s_e^{yx}, $\Delta_{e,q}$, and $\Gamma^q_{ek,k}$. Given these definitions and Eq. (11), the following relation between technical changes and factor prices is derived.

Lemma 5 *Given relative price p,*

1. *if* $s_k^{yx} > \frac{\left(\eta_{xe}\left(1-\Delta_{k,x}\cdot\Gamma^x_{ke,e}\right)-1\right)}{\left(\eta_{ye}\left(1-\Delta_{k,y}\cdot\Gamma^y_{ke,e}\right)-1\right)}\frac{\eta_{yk}}{\eta_{xk}}$ *then* $\frac{\partial \omega}{\partial \mu_y} < 0$.
2. *if* $s_e^{yx} > \frac{\left(\eta_{xk}\left(1-\Delta_{e,x}\cdot\Gamma^x_{ek,k}\right)-1\right)}{\left(\eta_{yk}\left(1-\Delta_{e,y}\cdot\Gamma^y_{ek,k}\right)-1\right)}\frac{\eta_{ye}}{\eta_{xe}}$ *then* $\frac{\partial \nu}{\partial \mu_y} < 0$.

Proof: The proof is relegated to Appendix B.

The conditions derived in Lemma 4 are, henceforth, denoted Condition 1. Lemma 4 tells us that a necessary condition for real wage ω to decline with technical changes in the capital good sector μ_y is that s_k^{yx} and s_e^{yx} are sufficiently large. Assuming energy and capital are complements, i.e., $\Gamma^x_{ke,e} > 0$, Condition 1 essentially requires that the curvature of the food production function with respect to capital and energy is sufficiently small, namely $\Delta_{k,x}$ and $\Delta_{e,x}$ are sufficiently large, in order for the real wage in terms of both capital and energy, i.e., ω and ν, to decline with technical changes.

Next, given Lemma 4, we illustrate that not only do wages decrease with neutral technical changes in production of manufactured goods, but also the labor-output ratio declines. Lemma 4 links technical changes to the real wage, whereas Proposition 6 links changes in the real wage to production of food, x, and manufactured goods, y.

Proposition 9 *Assume a neutral technical change in the production of manufactured goods, fix p, and assume condition (1) holds:*

1. *Then, if* $k_x < \min\{k_E, k_y\}$ *and* $0 < \partial k_x/\partial\omega < \partial k_E/\partial\omega < \partial k_y/\partial\omega$, *y increases and x decreases.*

2. *Similarly, if* $0 < \partial e_x/\partial\nu < \partial e_y/\partial\nu$, *y increases and x decreases.*

Proof: The Proof is relegated to Appendix B.

Neutral technical changes in production of manufacturing goods reduce the real wage and the quantity of food consumed, whereas it increases supply of the manufacturing goods. That is, the pattern of production changes at the expense of landless workers. Furthermore, because the manufactured goods are energy intensive, demand for energy increases, as do emissions. Therefore, technical changes in the production of manufactured goods lead to an increase in food prices. The reason: demand for biofuel increases, and first-generation biofuels compete with food for land.

5.2 Technical changes in the food sector

Now, we assume technical changes in production of food (henceforth, denoted ag biotech), where the equilibrium conditions become

$$p = \frac{1}{\mu_x} \cdot \frac{\partial \tilde{G}_y(.)/\partial k_y(.)}{\partial \widetilde{G}_x(.)/\partial k_x(.)} \text{ and } p = \frac{1}{\mu_x} \cdot \frac{\partial \tilde{G}_y(.)/\partial e_y(.)}{\partial \widetilde{G}_x(.)/\partial e_x(.)} \tag{10}$$

Ag biotech has the opposite effect on resource allocation of changes in production of manufactured goods.

Proposition 10 *Given a neutral technical change in production of food and given p, while assuming Condition 1,* $\frac{\partial\omega}{\partial\mu_x} > 0$. *Furthermore, if* $k_x < \min\{k_E, k_y\}$ *and* $0 < {}^{\partial k_x}/_{\partial\omega} < {}^{\partial k_E}/_{\partial\omega} < {}^{\partial k_y}/_{\partial\omega}$ *then x increases and y decreases. Similarly,* $\frac{\partial\nu}{\partial\mu_x} > 0$, *and if* $e_x < \min\{e_E, e_y\}$ *and* $0 < {}^{\partial e_x}/_{\partial\nu} < {}^{\partial e_y}/_{\partial\nu}$ *then x increases and y decreases.*

Recall neutral technical changes in manufactured goods reduce food production and increase food prices if Condition 1 holds. To weaken the linkage between the energy sector and the food sector, then, we seek technical changes in food production that make food production less concave.

While there have been a number of sources of agricultural productivity growth over the ages, including chemical fertilizer and pesticide use and irrigation technology in the middle of the 20th century and plant breeding of Green revolution in the 70s and 80s, it seems yield growth today will be driven by the Gene Revolution – the adoption of seed varieties that include genetically engineered traits to reduce pest damage and increase tolerance to drought and extreme weather. Since the mid-1990s, ag biotech has been shown to reduce the concavity of food production by genetically altering plants to induce either pest resistance or herbicide resistance. The technology, applied to cotton and, notably, corn, increases yield per acre while also reducing pesticide applications (e.g., Qaim and Zilberman, 2003; Huang et al. 2002; Qaim and de Janvry, 2005). Ag biotech can, therefore, represent a complimentary technology whose adoption alongside biofuel technology is consistent with goals of increasing renewable fuel production and reducing environmental damage.

5.3 Technical changes in the biofuel industry

Now, assume neutral technical changes in production of biofuel, and relax the small economy assumption. Then, the demand for energy and the supply of manufacture goods increase, whereas food supply decreases.

Proposition 11 *Given a neutral technical change in production of biofuel, assuming a big economy,* $\frac{y}{x}$ *increases and the price of food increases.*

To derive Proposition 11, assume neutral technical changes in the production of biofuel, and assume a big economy. Holding inputs constant, these changes imply a higher return to labor used to produce biofuel. Technical change in biofuel also increases the marginal productivity of land in biofuel. Then, the amount of land allocated for production of biofuel increases, as does labor. Energy supply shifts to the right. The cheaper supply of energy leads more firms to produce manufactured goods, and move away from the food sector (manufacture goods are energy intensive, contrary to food production). In the new equilibrium, the price of food increases and the supply of food decreases.

The second generation of biofuel, as opposed to the first generation biofuels based on ethanol from corn, sugar crops, and soy, aims to make biofuel production less land intensive and more efficient by relying on improved feedstocks such as cellulosic crops and algae. The second generation, therefore, may *reduce* the demand for land. Such technical changes, however, are not neutral, since they are targeted (partly) to reduce biofuel's dependence on land. Second generation biofuels are much more energy efficient and environmentally friendly (e.g., Rajagopal and Zilberman 2008). Whereas corn-based ethanol reduces emissions relative to fossil fuels by less than 20 percent (Farrell et al. 2006), some cellulostic based ethanol technologies are believed to reduce emissions relative to fossil fuels by as much as 90 percent.

6 Discussion and Concluding Remarks

In this paper, we introduce a framework for modeling the new energy paradigm characterized by rising energy prices and the emergence of a relatively clean, renewable energy alternative. It results seem consistent with recent patterns and provides new principles for policies to optimally manage energy and land resources.

The results suggest that globalization and capital flows result in new demand for energy and higher energy prices. They also increase demand for land, leading to a loss of environmental amenities and land allocated to food production - resulting in higher food prices. These effects are observed in China, for instance, where FDI and government investment have lifted overall investment in China and contributed to its growth. This growth produced sharp increases in demand for energy, and led China to become a major importer of oil. China also halted some biofuel production because the loss of land for food crops has produced record high food prices.

The linkage between energy, food and the environment can be lessened by technical change, but not just any technical change. Neutral technical changes in the production of the two final goods in this model have very different consequences for food supplies and the environment. First, neutral technical changes in the production of capital-intensive goods increases demand for energy and thereby increases demand for land for energy production. Second, neutral technical changes in the production of biofuel, such as improvements in biofuel crop technology, improve the productivity of land, which should lessen the land constraint. However, such innovation also increases biofuel production, which generates greater demand for land in biofuel. Biotechnology *specific* to biofuel production, therefore, may have a negative effect on food supplies and the environment. The second generation of biofuel using cellulosic feedstocks promises to reduce the competition for land between food and energy production and reduce overall demand for land through productivity gains. Agricultural biotechnology unambiguously reduces the land constraint and attenuates the impacts of biofuel adoption on food supply and land allocations. Investment in agricultural biotechnology has slowed, however, in part because of regulation and bans in Europe and elsewhere *(Just et al. 2007)*. These results suggest a new commitment to agricultural biotechnology, as well as second generation biofuels, may be needed to address the new energy paradigm. Such policies would be consistent with heightened environmental concern in the developed world.

Many countries, and multinational institutions, are considering imposing or have imposed carbon taxes or similar policies. We show that carbon tax may result in loss of welfare, if it is not accompanied by taxes on land conversion, taxes that internalize the social cost from loss of biodiversity and open space. Likewise, a land tax absent a carbon tax can be suboptimal to the environment. In fact, we show that a land tax and a carbon tax are (imperfect) substitutes. If one is set too low, the other is optimally set too high (relative to the social optimum). Thus the complexity of the interactions between agricultural, industrial, and environmental systems makes designing efficient polices to address climate change a major challenge, and may require further research collaboration between economists and scientists in other discipline. Our analysis did not consider the uncertainties associated with climate change research. Further research should address policy design and resulting trade implications, when the uncertainties associated with climate change are considered.

7 Appendices

7.1 Appendix A

7.1.1 Dimensionality

The initial step, in which the dimensionality of our problem is reduced, is now formally solved. Assume producers minimize the cost of production and are price takers. Their problem can be described as follows:

$$\max_{\{L_q, A_q, K_q, E_q\}} \quad \{p_q \cdot g_q\left(L_q, A_q, K_q, E_q\right) - w \cdot L_q - s \cdot A_q - r \cdot K_q - p_E \cdot E_q\} \tag{11}$$

By rearranging the terms, an alternative statement of the firms problem is obtained:

$$\max_{\{L_q, K_q, E_q\}} \quad \left\{p_q \cdot \max_{A_q} \left\{g_q\left(L_q, A_q, K_q, E_q\right) - \frac{s}{p_q} \cdot A_q\right\} - w \cdot L_q - r \cdot K_q - p_E \cdot E_q\right\}.$$

As defined in Section 3.1, $s_q = \frac{s}{p_q}$ is the real rent of land in terms of good q and

$$G_q\left(L_q, K_q, E_q, s_q\right) \equiv \max_{A_q} \{g_q\left(L_q, A_q, K_q, E_q\right) - s_q \cdot A_q\}. \tag{12}$$

The solution to Eq. (12) is $A_q = H_q\left(L_q, K_q, E_q, s_q\right)$. A_q can be interpreted as the derived demand for land by sector q, given the real rent to land, and given labor, capital, and energy.[22] Because $g_q\left(L_q, A_q, K_q, E_q\right)$ is linearly homogeneous, the derived demand H_q is linearly homogeneous in K_q, L_q, and E_q, given s_q. This means that $G_q\left(L_q, K_q, E_q, s_q\right)$ is also homogeneous of degree one in K_q, L_q, and E_q, given s_q.

We now argue that $G_q\left(L_q, K_q, E_q, s_q\right)$ behaves like a production function: While utilizing the envelope theorem, we can show that the derivatives of $G_q\left(L_q, K_q, E_q, s_q\right)$ with respect to labor, capital, or energy are equal to the corresponding derivatives of $g_q\left(L_q, A_q, K_q, E_q\right)$. It can also be shown that given s_q, $G_q\left(L_q, K_q, E_q, s_q\right)$ is concave in L_q, K_q, and E_q.

Thus, the profit maximization problem, as depicted in Eq. (11), can be rewritten as

$$\max_{\{L_q, K_q, E_q\}} \quad \{p_q \cdot G_q\left(L_q, K_q, E_q, s_q\right) - w \cdot L_q - r \cdot K_q - p_E \cdot E_q\}$$

The land factor plays an indirect role through its effect on the real rent to land.

[22] A similar role is played by capital, if instead of endogenously determining the amount of land allocated to production, we assume free capital movement between countries (see Wong, 1995).

7.1.2 The Equilibrium

To derive the equilibrium, start with a given s, and let $s_q \equiv \frac{s}{p_q}$. Then, since production functions are homogenous of degree one in capital, labor, and energy,

$$G_q\left(K_q, L_q, E_q, s_q\right) \equiv L_q \cdot G_q\left(\frac{K_q}{L_q}, 1, \frac{E_q}{L_q}, s_q\right) \equiv L_q \cdot \widetilde{G}_q\left(\, k_q, e_q, s_q\right),$$

where $k_q = \frac{K_q}{L_q}$ denotes the capital-labor ratio and $e_q = \frac{E_q}{L_q}$ denotes the energy-labor ratio.

The Inada Conditions imply that $\frac{MP_q^L}{MP_q^K}$ goes to 0 (∞) as the capital-labor ratios k_q tends to 0 (∞). Similarly, $\frac{MP_q^L}{MP_q^E}$ goes to 0 (∞) as the energy-labor ratios e_q tends to 0 (∞). The Inada conditions imply that, given s_q, the optimal capital-labor ratios k_q and energy-labor ratios e_q are unique functions of $\omega \equiv \frac{w}{r}$ and $\nu \equiv \frac{p_E}{r}$ and are implicitly given by

$$\begin{aligned}
\frac{MP_x^K}{MP_x^L} &= \frac{\frac{\partial}{\partial k_x}\left(\widetilde{G}_x(k_x,e_x,s_q)\right)}{\left[\widetilde{G}_x(k_x,e_x,s_q)-k_x\cdot\frac{\partial}{\partial k_x}\left(\widetilde{G}_x(k_x,e_x,s_q)\right)-e_x\cdot\frac{\partial}{\partial e_x}\left(\widetilde{G}_x(k_x,e_x,s_q)\right)\right]} = \omega,\\
\frac{MP_y^K}{MP_y^L} &= \frac{\frac{\partial}{\partial k_y}\left(\widetilde{G}_y\left(k_y,e_y,s_q\right)\right)}{\left[\widetilde{G}_y\left(k_y,e_y,s_q\right)-k_y\cdot\frac{\partial}{\partial k_y}\left(\widetilde{G}_y\left(k_y,e_y,s_q\right)\right)-e_y\cdot\frac{\partial}{\partial e_y}\left(\widetilde{G}_y\left(k_y,e_y,s_q\right)\right)\right]} = \omega,\\
\frac{MP_x^E}{MP_x^L} &= \frac{\frac{\partial}{\partial e_x}\left(\widetilde{G}_x(k_x,e_x,s_q)\right)}{\left[\widetilde{G}_x(k_x,e_x,s_q)-k_x\cdot\frac{\partial}{\partial k_x}\left(\widetilde{G}_x(k_x,e_x,s_q)\right)-e_x\cdot\frac{\partial}{\partial e_x}\left(\widetilde{G}_x(k_x,e_x,s_q)\right)\right]} = \nu, \text{ and}\\
\frac{MP_y^E}{MP_y^L} &= \frac{\frac{\partial}{\partial e_y}\left(\widetilde{G}_y\left(k_y,e_y,s_q\right)\right)}{\left[\widetilde{G}_y\left(k_y,e_y,s_q\right)-k_y\cdot\frac{\partial}{\partial k_y}\left(\widetilde{G}_y\left(k_y,e_y,s_q\right)\right)-e_y\cdot\frac{\partial}{\partial e_y}\left(\widetilde{G}_y\left(k_y,e_y,s_q\right)\right)\right]} = \nu.
\end{aligned}$$

Lemma 1A (The Lerner conditions): k_q and e_q for $q \in \{x, y\}$ can be written as a function of only ω, υ, and s_q.

Next, we show that the price of food, p, together with the land tax Ψ, and the carbon tax Φ, determine s, ω, and υ uniquely. The unit cost of sector q then equals $r \cdot a_{K_q} + w \cdot a_{L_q} + s \cdot a_{A_q} + p_E \cdot a_{E_q}$ (assuming land is allocated both to production and to the environment). Positive output and zero profits imply in equilibrium

$$\begin{aligned}
p &= r \cdot a_{K_x} + w \cdot a_{L_x} + s \cdot a_{A_x} + p_E \cdot a_{E_x}, \text{ and}\\
1 &= r \cdot a_{K_y} + w \cdot a_{L_y} + s \cdot a_{A_y} + p_E \cdot a_{E_y}.
\end{aligned} \tag{13}$$

Assume production of both fossil fuel and biofuel in equilibrium.[23] Then

$$r \cdot a_{K_E^f} + w \cdot a_{L_E^f} + \Phi \cdot \frac{\partial g_z}{\partial E} = p_E = s \cdot a_{A_E^b} + w \cdot a_{L_E^b} + \rho \cdot \Phi \cdot \frac{\partial g_Z}{\partial E}. \tag{14}$$

Because the land tax is strictly positive and $\overline{A} - A_N > 0$, $s = \Psi + \Phi \cdot \frac{\partial g_Z}{\partial A_n}$ in equilibrium. Pressure to change s is mitigated by a change in the amount of land allocated to production, $\overline{A} - A_N$.

[23] Note that, contrary to the assumptions made about sectors x and y, biofuel production may be zero. Hence, in equilibrium $p_E - \Phi \cdot \frac{\partial g_Z}{\partial E} = r \cdot a_{K_E^f} + w \cdot a_{L_E^f}$ whereas $p_E < s \cdot a_{A_E^b} + w \cdot a_{L_E^b} + \rho \cdot \Phi \cdot \frac{\partial g_Z}{\partial E}$.

7.2 Appendix B

Proof of Proposition 1

Specifically, fix the land tax and the carbon tax. Because commodity and factor prices are fixed, the capital-labor ratio is unchanged. The capital resource constraint in Eq. (6), then, equals

$$\hat{k}_y \cdot L_y + \hat{k}_E \cdot L_E + \hat{k}_x \cdot \left[\overline{L} - L_y - L_E\right] = \hat{\bar{K}},$$

where a caret ($\hat{}$) above a variable denotes a proportional change. Hence, and given $\hat{k}_x < \min\left\{\hat{k}_E, \hat{k}_y\right\}$, $\frac{\partial L_y}{\partial \hat{\bar{K}}} = \frac{1}{\hat{k}_y - \hat{k}_x} > 0$, and $\frac{\partial L_E}{\partial \hat{\bar{K}}} = \frac{1}{\hat{k}_E - \hat{k}_x} > 0$. Then it can be shown that

$$\begin{aligned}
\frac{\partial y}{\partial \hat{\bar{K}}} &= \frac{\tilde{G}_y\left(\hat{k}_y, \widehat{e}_y, \Psi_y\right)}{\hat{k}_y - \hat{k}_x} > 0, \\
\frac{\partial E^f}{\partial \hat{\bar{K}}} &= \frac{\tilde{G}_{E^f}\left(\hat{k}_{E^f}, \Psi_{E^f}\right)}{\hat{k}_E - \hat{k}_x} > 0, \text{and} \\
\frac{\partial x}{\partial \hat{\bar{K}}} &= \frac{-\left(\hat{k}_y - \hat{k}_x + \hat{k}_E - \hat{k}_x\right)\tilde{G}_x\left(\hat{k}_x, \widehat{e}_x, \Psi_x\right)}{\left(\hat{k}_y - \hat{k}_x\right)\left(\hat{k}_E - \hat{k}_x\right)} < 0,
\end{aligned}$$

which is the Rybczynski effect.

Proof of Proposition 2

First, we express goods consumed and produced in terms of their factor content.[24] Then, if factor prices and taxes are equalized, the proof draws from Staiger (1986), which shows that, on average, if factor prices are equalized then the different countries export services of the abundant factor. When, on the other hand, commodity prices and/or taxes are not equalized, the proof follows Brecher and Choudhri (1982) and Helpman (1984), which show that, on average, country exports services of the factors that are cheaper under free trade. See also Wong, 1995 and Bhagwati et al., 1998.

Proof of Lemma 3:

Differentiate Eq. (12) with respect to ω and μ_y, while using the implicit function theorem, and rearrange terms

$$\frac{\partial \omega}{\partial \mu_y} = \frac{1}{\mu_y}\left[\frac{\frac{\partial^2 \widetilde{G}_x(.)}{\partial k_x^2}\frac{\partial k_x}{\partial \omega}}{\frac{\partial \widetilde{G}_x(.)}{\partial k_x}} - \frac{\frac{\partial^2 \widetilde{G}_y(.)}{\partial k_y^2}\frac{\partial k_y}{\partial \omega}}{\frac{\partial \widetilde{G}_y(.)}{\partial k_y}}\right]^{-1}.$$

The ratio of the marginal return to labor and the marginal return to capital equalsω, i.e.,

$$\frac{\widetilde{G}_x(.) - k_x \frac{\partial \widetilde{G}_x(.)}{\partial k_x} - e_x \frac{\partial \widetilde{G}_x(.)}{\partial e_x}}{\frac{\partial \widetilde{G}_x(.)}{\partial k_x}} = \omega = \frac{\widetilde{G}_y(.) - k_y \frac{\partial \widetilde{G}_y(.)}{\partial k_y} - e_y \frac{\partial \widetilde{G}_y(.)}{\partial e_y}}{\frac{\partial \widetilde{G}_y(.)}{\partial k_y}}.$$

[24] This approach dates back to Leontief (1953) and his famous test of the Heckscher-Ohlin Theorem, later formalized theoretically by Travis (1964), Vanek (1963), Melvin (1968). These results were extended by Horiba (1974), Leamer (1980), Brecher and Choudhri (1982), Trefler (1993), and most recently by Davis, Weinstein, Bradford, and Shimpo (1997) and Davis and Weinstein (1996).

We now use this relation to compute $\frac{\partial\, k_x}{\partial \omega}$ and $\frac{\partial\, k_y}{\partial \omega}$:

$$
\begin{aligned}
\frac{\partial\, k_x}{\partial \omega} &= \left[\frac{\left(e_x \left(\frac{\partial\, \widetilde{G}_x(.)}{\partial e_x} \frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} - \frac{\partial^2\, \widetilde{G}_x(.)}{\partial e_x \partial\, k_x} \frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x} \right) - \widetilde{G}_x(.) \frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} \right)}{\left(\frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x} \right)^2} \right]^{-1} \text{ and} \\
\frac{\partial\, k_y}{\partial \omega} &= \left[\frac{\left(e_y \left(\frac{\partial\, \widetilde{G}_y(.)}{\partial e_y} \frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} - \frac{\partial^2\, \widetilde{G}_y(.)}{\partial e_y \partial\, k_y} \frac{\partial\, \widetilde{G}_y(.)}{\partial\, k_y} \right) - \widetilde{G}_y(.) \frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} \right)}{\left(\frac{\partial\, \widetilde{G}_y(.)}{\partial\, k_y} \right)^2} \right]^{-1}.
\end{aligned}
$$

Then,

$$
\begin{aligned}
&\frac{\partial \omega}{\partial \mu_y} < 0 \Leftrightarrow \frac{1}{\mu_y} \left[\frac{\frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} \frac{\partial k_x}{\partial \omega}}{\frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x}} - \frac{\frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} \frac{\partial k_y}{\partial \omega}}{\frac{\partial\, \widetilde{G}_y(.)}{\partial\, k_y}} \right]^{-1} < 0 \Leftrightarrow \\
&\frac{\frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} \frac{\partial k_x}{\partial \omega}}{\frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x}} < \frac{\frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} \frac{\partial k_y}{\partial \omega}}{\frac{\partial\, \widetilde{G}_y(.)}{\partial\, k_y}} < 0
\end{aligned}
$$

Hence, as

$$
\begin{aligned}
&\frac{\frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} \frac{\partial k_x}{\partial \omega}}{\frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x}} < \frac{\frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} \frac{\partial k_y}{\partial \omega}}{\frac{\partial\, \widetilde{G}_y(.)}{\partial\, k_y}} \Leftrightarrow \\
&\frac{\frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} \frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x}}{\left(e_x \left(\frac{\partial\, \widetilde{G}_x(.)}{\partial e_x} \frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} - \frac{\partial^2\, \widetilde{G}_x(.)}{\partial e_x \partial\, k_x} \frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x} \right) - \widetilde{G}_x(.) \frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} \right)} < \\
&\frac{\frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} \frac{\partial\, \widetilde{G}_y(.)}{\partial\, k_y}}{\left(e_y \left(\frac{\partial\, \widetilde{G}_y(.)}{\partial e_y} \frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} - \frac{\partial^2\, \widetilde{G}_y(.)}{\partial e_y \partial\, k_y} \frac{\partial\, \widetilde{G}_y(.)}{\partial\, k_y} \right) - \widetilde{G}_y(.) \frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} \right)}
\end{aligned}
$$

where

$$
\begin{aligned}
&\frac{\frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} \frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x}}{\left(e_x \frac{\partial\, \widetilde{G}_x(.)}{\partial e_x} \frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} - \widetilde{G}_x(.) \frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} - e_x \frac{\partial^2\, \widetilde{G}_x(.)}{\partial e_x \partial\, k_x} \frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x} \right)} \\
&= \frac{\frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} \frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x} \frac{1}{\widetilde{G}_x(.)}}{\left(\frac{e_x}{\widetilde{G}_x(.)} \frac{\partial\, \widetilde{G}_x(.)}{\partial e_x} \frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} - \frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} - \frac{e_x}{\widetilde{G}_x(.)} \frac{\partial^2\, \widetilde{G}_x(.)}{\partial e_x \partial\, k_x} \frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x} \right)} \\
&= \frac{\frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} \frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x} \frac{k_x}{\widetilde{G}_x(.)} \frac{1}{k_x}}{\frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2} \left(\frac{e_x}{\widetilde{G}_x(.)} \frac{\partial\, \widetilde{G}_x(.)}{\partial e_x} - 1 - \frac{e_x}{\widetilde{G}_x(.)} \frac{\partial\, \widetilde{G}_x(.)}{\partial e_x} \frac{\frac{\partial^2\, \widetilde{G}_x(.)}{\partial e_x \partial\, k_x}}{\frac{\partial^2\, \widetilde{G}_x(.)}{\partial\, k_x^2}} \frac{\frac{\partial\, \widetilde{G}_x(.)}{\partial\, k_x}}{\frac{\partial\, \widetilde{G}_x(.)}{\partial e_x}} \right)} \\
&= \frac{\eta_{xk} \frac{1}{k_x}}{\left(\eta_{xe} \left(1 - \Delta_{k,x} \cdot \Gamma^x_{ke,e} \right) - 1 \right)}
\end{aligned}
$$

and

$$
\frac{\frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} \frac{\partial\, \widetilde{G}_y(.)}{\partial\, k_y}}{\left(e_y \left(\frac{\partial \widetilde{G}_y(.)}{\partial e_y} \frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} - \frac{\partial^2\, \widetilde{G}_y(.)}{\partial e_y \partial\, k_y} \frac{\partial\, \widetilde{G}_y(.)}{\partial\, k_y} \right) - \widetilde{G}_y(.) \frac{\partial^2\, \widetilde{G}_y(.)}{\partial\, k_y^2} \right)} = \frac{\eta_{yk} \frac{1}{k_y}}{\left(\eta_{ye} \left(1 - \Delta_{k,y} \cdot \Gamma^y_{ke,e} \right) - 1 \right)},
$$

we get

$$
\begin{aligned}
&\frac{\partial \omega}{\partial \mu_y} < 0 \Leftrightarrow \frac{\eta_{xk} \frac{1}{k_x}}{\left(\eta_{xe} \left(1 - \Delta_{k,x} \cdot \Gamma^x_{ke,e} \right) - 1 \right)} < \frac{\eta_{yk} \frac{1}{k_y}}{\left(\eta_{ye} \left(1 - \Delta_{k,y} \cdot \Gamma^y_{ke,e} \right) - 1 \right)} < 0 \\
&\Leftrightarrow s_k^{yx} > \frac{\left(\eta_{xe} \left(1 - \Delta_{k,x} \cdot \Gamma^x_{ke,e} \right) - 1 \right)}{\left(\eta_{ye} \left(1 - \Delta_{k,y} \cdot \Gamma^y_{ke,e} \right) - 1 \right)} \frac{\eta_{yk}}{\eta_{xk}}
\end{aligned}
$$

Lemma 3 follows (recall that $\frac{\partial^2\, \widetilde{G}_q(.)}{\partial\, k_q^2} < 0 < \frac{\partial\, \widetilde{G}_q(.)}{\partial\, k_q}$, and therefore $\eta_{xk} > 0$ and $\eta_{yk} > 0$). Similar techniques can be used to prove that if $s_e^{yx} > \frac{\left(\eta_{xk} \left(1 - \Delta_{k,x} \cdot \Gamma^x_{ke,e} \right) - 1 \right)}{\left(\eta_{yk} \left(1 - \Delta_{k,y} \cdot \Gamma^y_{ke,e} \right) - 1 \right)} \frac{\eta_{ek}}{\eta_{ek}}$ then $\frac{\partial \nu}{\partial \mu_y} < 0$.

Q.E.D.

Proof of Proposition 7:

We exploit the full-employment conditions to derive x and y, i.e.,

$$\begin{aligned} x &= L_x \cdot \widetilde{G_x}\left(.\right) = \tfrac{\left[\overline{K}-\left(\overline{L}-L_y\right)\cdot k_E - L_y k_y\right]}{k_x - k_E} \cdot \widetilde{G_x}\left(.\right) \text{and} \\ y &= L_y \cdot \widetilde{G}_y\left(.\right) = \tfrac{\left[\overline{K}-\left(\overline{L}-L_x\right)\cdot k_E - L_x k_x\right]}{k_y - k_E} \cdot \widetilde{G}_y\left(.\right), \end{aligned}$$

and show that $\frac{\partial x}{\partial \omega} > 0$ and $\frac{\partial y}{\partial \omega} < 0$. To this end, note that

$$\begin{aligned} \tfrac{\partial}{\partial \omega}\left[\overline{K} - \left(\overline{L} - L_y\right) \cdot k_E - L_y k_y\right] &= -\left(\overline{L} - L_y\right) \cdot \tfrac{\partial k_E}{\partial \omega} - L_y \tfrac{\partial k_y}{\partial \omega} < 0 \text{and} \\ \tfrac{\partial}{\partial \omega}\left[\overline{K} - \left(\overline{L} - L_x\right) \cdot k_E - L_x k_x\right] &= -\left(\overline{L} - L_x\right) \cdot \tfrac{\partial k_E}{\partial \omega} - L_x \tfrac{\partial k_x}{\partial \omega} < 0, \end{aligned}$$

because $k_x < \min\{k_E, k_y\}$ and $0 < {}^{\partial k_x}/_{\partial \omega} < {}^{\partial k_E}/_{\partial \omega} < {}^{\partial k_y}/_{\partial \omega}$ by assumption, and recall that neutral technical changes in the production of capital cause ω to decline (Lemma 4). Therefore, given neutral technical changes in the production of capital, x declines and y increases. Similar techniques can be used to prove $\frac{\partial x}{\partial \nu} > 0$ and $\frac{\partial y}{\partial \nu} < 0$.

Q.E.D.

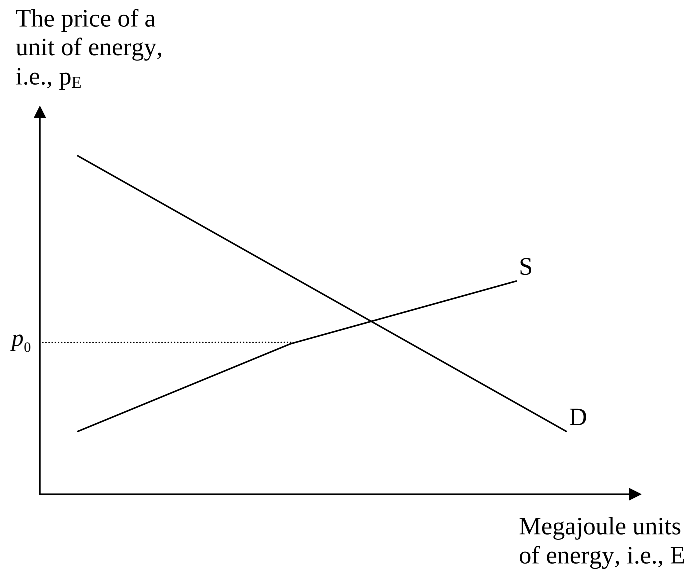

Figure 1: The energy market

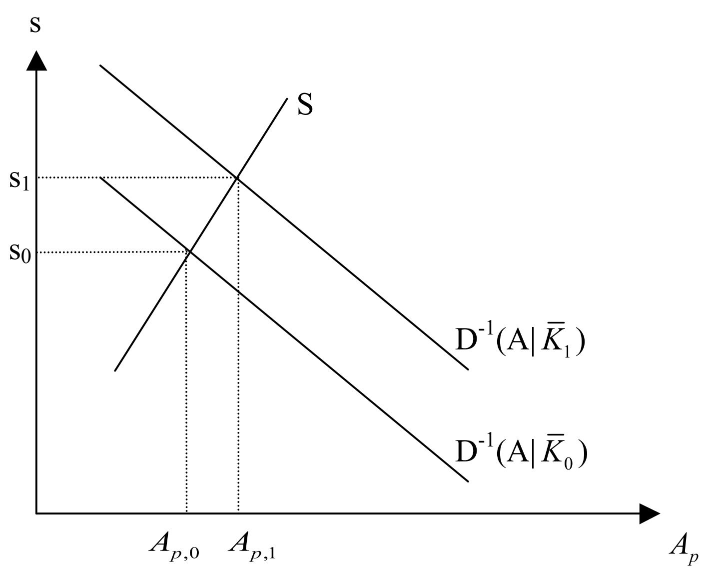

Figure 2: Demand for Land for Production

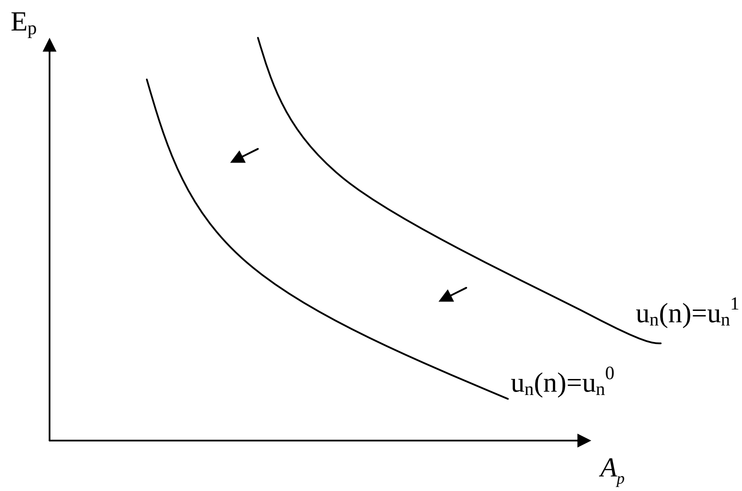

Figure 3: The Environment Indifferent Curve

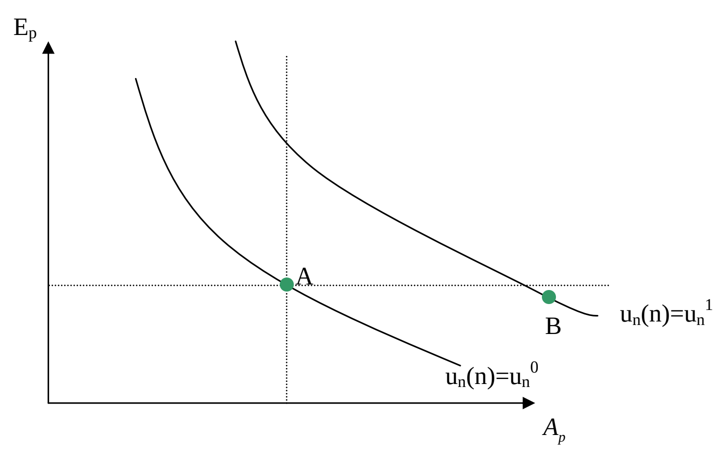

Figure 4: The Environment Indifferent Curves and Comparative Static