The Economics of Trade, Biofuel, and the Environment

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Abstract

This work develops a general equilibrium framework to analyze changes in the energy sector within a global environment. It extends traditional trade models to consider issues of energy and the environment by introducing energy as a ubiquitous intermediate input in a general equilibrium trade model and by using a household model with energy entering directly into consumer decisions. This yields a framework to consider energy and climate change policy considerations. Recognizing the supply constraints on energy, the conditions which lead to the emergence of a biofuel sector, and the impact of these changes on prices, resource allocation and the pattern of trade are identified. Globalization and capital flow are shown to increase demand for energy, leading to a decline in food production and loss of environmental land. It is also shown that whereas neutral technical change in capital-intensive goods escalates tension between energy, food and the environment, neutral technical change in agricultural production, such as biotechnology and

second generation biofuel technologies, mitigates this pressure.

1. Introduction

Energy is a commodity whose importance to the world community is second only to food. It is a ubiquitous factor in the production and consumption of most commodities, from heaters and hairdryers to cars and computers. Firms use energy to produce consumption goods, which consumers then combine with energy to generate utility, such as from transportation and heating. A conservative "back of the envelope" calculation attributes 22 percent of all U.S. energy consumption to households and 32 percent of all US (and 8 percent of all world) carbon emissions to individuals.[1,2] This ubiquity necessitates a household production function model, which heretofore, has not been applied to energy.

For most of the 20th century, non-renewable, non-recyclable petroleum has been the primary source of energy around the world. In response to the growing scarcity of fossil fuels and rising oil prices and motivated by concern over the environmental damage created by fossil fuel consumption, demand for renewable and clean energy is growing. In this context, biofuels have emerged as a promising new technology that can reduce dependency on traditional fossil fuel technology. Currently, biofuel is produced by the conversion of corn and sugar cane to ethanol or soy and palm oil to bio-diesel. It is hoped new technologies will be capable of converting cellulose crops, such as trees and grasses, into ethanol through processes that yield

[1] 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" (Transortation Energy Data Book Edition 26-2007, Oak Ridge National Laboratory). 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 residences.

greater net energy content. Today, biofuel is in its infancy and the bulk of the demand for biofuels is regulation-induced. Problems of adjustment from fossil fuel to biofuel slow adoption and create a role for policy.

In this paper, we examine these local and global effects of the emerging paradigm-shift in energy. In addition to modeling energy as a ubiquitous good used by producers and consumers, we also model a renewable alternative that reduces some environmental externalities. The renewable technology is land intensive, and, therefore, introduces new environmental externalities. We show globalization and capital inflows lead to increased demand for energy. Assuming energy production from fossil fuel and biofuel, it is shown that greater demand for energy reduces land allocated to food production and yields higher food prices. While biofuel production yields environmental benefits by reducing build up of greenhouse gases, it also imposes environmental damage in the form of deforestation and biodiversity loss.[3]

Innovation can have significant effects on the environment, agriculture and energy, either strengthening the tension among the three or reducing it. Understanding these impacts, therefore, is important. For instance, technical change in the production of capital-intensive goods increases demand for energy, thereby reducing the allocation of land to food production and the environment. Also, although it is generally assumed agricultural biotechnology increases food production, we show that improvements in crop technology applied to biofuel crops may reduce land allocated for food. Improvements in food crop technology, however, unambiguously increase food production and alleviate the tension between food and energy.

Formally, we assume a two-country model, with identical constant return to scale production technologies and identical homothetic preferences. Both countries are endowed with

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[2] Vandenbergh and Steinemann (2007).

[1] Farrell, et al. (2006) estimate corn ethanol reduces greenhouse gas emissions “moderately” by 13 percent.

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.

The economic structure, therefore, builds on work (originated by Samuelson (1953), and extended by Melvin (1968), Drabicki and Takayama (1979), Dixit and Norman (1980), Deardroff (1980), Dixit and Woodland (1982), and many others) that 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).[4] It investigates the accuracy of the classical trade theorems: the Rybczynski theorem, the Stopler-Samuelson theorem, the Heckscher-Ohlin theorem, and the factor price equalization theorem.[5]

In introducing energy at the household level, we draw on the literature of household production functions (e.g., the seminal work by Becker, 1965, and Lancaster, 1966). Specifically, the household production function produces utility units from "convenience goods" that are produced by the combination of capital goods and energy. For example, petroleum is used to produce a car and then used by a consumer to derive utility from the car. This framework also introduces a non-traded good, i.e. a convenience good. This work, therefore, extends Becker's work by considering energy, instead of time, as an input needed to produce the final good at the

[4] To this end, some authors generalized the law of one price to cases in which there are many goods and only two factors (e.g., Jones, 1956-1957, Bhagwati, 1972, and Deardorff, 1979).

[5] Jones (1977) noted that there are two approaches to generalizing the results of a two-by-two theory to many-goods many-factors models. The first looks for additional restrictions on technology that extends the two-by-two model to many-goods many-factors. The second makes the same general assumptions as in the standard two-by-two theory and look for weaker results that are as close to the standard results as possible. This approach, which was pioneered by Chipman (1969) and Uekawa (1971), leads to very limited results, as argued by Bhagwati et al. (1998) (see also

household level. It is also related to Lancaster (1965) because it abstracts from the tension between leisure and work.

This analysis is also related to the literature on trade in tasks, in which the many tasks required to manufacture complex industrial goods are performed in several, disparate locations, through what is popularly known as "offshoring" (e.g., Grossman and Rossi-Hansberg (2006a and 2006b), Grossman and Helpman (2005), Antras and Helpman (2004)).[6] The production process in the paper is performed in several, disparate locations because energy is a traded intermediate input. This work, however, differs from that literature in at least two aspects: (i) it does not focus on tasks, but rather on physical intermediate goods, and (ii) it models a ubiquitous factor used at all stages of production.

The economic structure is described in Section 2 and the dimensions of the problem are reduced in Section 3. The (trade) equilibrium is derived in Section 4 and the importance of capital accumulation is modeled and discussed in Section 5. Technical changes are introduced in Section 6, and a discussion and concluding remarks are offered in Section 7.

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 (denoted respectively by no superscript and by an asterisk), three factors and four (intermediate) goods, in which (i) all markets are

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Dixit and Norman, 1980, and Ethier, 1984, among many others).

[6] The popular press is replete with stories of task trade: Tempest (1996), for example, describes the global process for producing a Barbie doll. Burrows (1995) tell a similar story about Texas Instruments' high-speed telecommunications chip. Almost daily we read media stories of companies in India that answer customer service calls (Friedman, 2004), read x-rays (Pollak, 2003), develop software (Thurm, 2004), prepare tax forms (Robertson et

competitive, (ii) free trade prevails, and (iii) there are no transaction costs. One of the goods, a convenience good, 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). The utility function is additive, where the commodities are convenience goods, c, an environmental commodity, n, and food, x.[7] Similar to Becker (1965), commodities are concrete and physical. However, we assume activity combines energy and capital goods and transforms them into convenience goods. Whereas Becker's commodities distinguished between an omelet cooked at home and one served at a restaurant, this work distinguishes, for instance, between buying a television and watching television.

Convenience goods, i.e., commodities that supply the household with convenience and fun, are produced from capital products, y (e.g., car, computers, or homes), and energy E_c, where $g_c\left(y, E_c\right)$ denotes the *activity* that combines capital goods and energy and *transforms* them into convenience goods, i.e., $c = g_c\left(y, E_c\right)$ (a la Lancaster 1965). We assume that $g_c\left(y, E_c\right)$

al., 2005) and even perform heart surgery on American patients (Baker et al., 2006). Blinder (2006) refers to the expanding feasibility of offshoring formerly non-tradable services as the "Third Industrial Revolution."

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

is increasing and concave in its arguments, and is homogeneous of degree one.

The environmental commodity's "production function" is denoted $n \equiv g_n(A_n, Z)$, where A_n is nature, as measured by biodiversity or pristine land, and Z is pollution (e.g., green house gases). This function is assumed to be concave in both arguments, where $\frac{\partial g_n}{\partial A_n} > 0$ and. For the sake of simplicity, we assume the food commodity equals purchased food products x.

2.1.1 Consumers

Consumers maximize a separable additive utility function

$$U = u_x(x) + u_y(c) + u_n(n).$$

Sub-utility $u_x(x)$ is concave, i.e., $\frac{\partial u_x}{\partial x} > 0$ and $\frac{\partial^2 u_x}{\partial x^2} < 0$, and so are $u_c(c)$ and $u_n(n)$. Also, assume all goods are normal goods.

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 capital goods to 1 (and henceforth let $p \equiv p_x / p_y$). Consumers take disposable income I as given. Hence, the budget constraint can be written as

$$p_x \cdot x + p_c \cdot c \leq I,$$

where $p_c \equiv a_{y,c} + a_{E_c,c} \cdot p_E$ and where a_{ji} denotes the cost-minimizing amount of factor j used to produce one unit of good i; in other words,

$$c_c(p_E) = \min_{\{a_{jc}\}_{j \in \{y, E_c\}}} \left\{ a_{yc} + p_E \cdot a_{E_c c} : g_c(a_{yc}, a_{E_c c}) \geq 1 \right\}.$$

In other words, 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 goods. 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:

$$E^f = \begin{cases} g_E^f\left(L_E{}^f, K_E^f\right) & g_E^f\left(L_E{}^f, K_E^f\right) < \bar{E}^f \\ \bar{E}^f & \text{otherwise} \end{cases}$$

and

$$E^b = g_E^b\left(L_E{}^b, A_E^b\right),$$

where production of fossil fuel is capacity constrained, i.e., $\bar{E}^f > 0$. Superscripts f and b denote fossil fuel and biofuel, respectively. In addition, 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. Also, extracting energy from fossil fuel is a polluting process; the pollution "production function" is $Z \equiv g_Z\left(E^f\right)$, such that $\frac{\partial g_Z}{\partial E^f} > 0$.

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

$$x = g_x\left(L_x, K_x, A_x, E_x\right) \text{ and } y = g_y\left(L_y, K_y, A_y, E_y\right). \tag{1}$$

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 $\bar{L}$, $\bar{K}$, and $\bar{A}$. Therefore, the economy's resource constraints are

[8] We assume that the conditions required for two step maximization hold (See Green 1964).

$$\overline{K} = K_E + K_x + K_y,$$
$$\overline{L} = L_E + L_x + L_y, \text{ and} \tag{2}$$
$$\overline{A} = A_E + A_x + A_y + A_n$$

In addition, assume all land is initially allocated to the environment, and can be used for production after a conversion cost $\Psi > 0$ is paid. Assume also that *E*, *x*, and *y*, are traded goods.

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 unit cost function (i.e., the minimum per-unit cost of production of a good as a function of factor prices) is

$$c_q(w, s, r, p_E) = \min_{\{a_{Lq}, a_{Aq}, a_{Kq}, a_{Eq}\}} \left\{ w \cdot a_{Lq} + s \cdot a_{Aq} + r \cdot a_{Kq} + p_E \cdot a_{Eq} \ : g_q\left(a_{Lq}, a_{Aq}, a_{Kq}, a_{Eq}\right) \geq 1 \right\} \tag{3}$$

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

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

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

3. Dimensionality

Our first goal is to analyze the trade model, given that a non-traded good is produced at the household level. We work toward this goal in two steps: First, we assume that allocation of land maximizes a firm's profits, and we use this argument to rewrite the production functions of *x* and *y* as a function of capital, land, energy, and the conversion cost only.[9] We apply these techniques to our setting, given that land can be used either for production or for nature. Second, and after reducing the dimensionality of our problem, we use techniques developed by numerous trade theorists to derive the equilibrium, and find the equilibrium prices and allocation of resources between the different sectors.

The initial step, in which the dimensionality of our problem is reduced, is solved formally in Appendix A. To this end, let $s_q = \frac{s}{p_q}$ be the real rent of land in terms of good *q*, and define $G_q\left(L_q, K_q, E_q, s_q\right) \equiv \max_{A_q}\left\{p_q \cdot g_q\left(L_q, A_q, K_q, E_q\right) - s \cdot A_q\right\}$. Then, it is shown that the profit maximization problem can be rewritten as

$$\max_{\{L_q, K_q, E_q\}} \left\{p_q \cdot G_q\left(L_q, K_q, E_q, s_q\right) - w \cdot L_q - r \cdot K_q - p_E \cdot E_q\right\} \qquad (4)$$

The land factor plays an indirect role through its effect on the real rent to land.[10]

4. The Equilibrium

In Section 4.1 the autarky equilibrium is derived, given a conversion cost Ψ. In Section 4.2 the free trade equilibrium is derived under the assumption that $\Psi = \Psi^*$, an assumption that is relaxed in Section 4.3 where it is assumed that $\Psi \neq \Psi^*$.

4.1. The Autarky Equilibrium

[9] 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): the Rybczynski theorem, the Stopler-Samuelson theorem, the Heckscher-Ohlin theorem, and the factor price equalization theorem.
[10] 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).

To derive the equilibrium, start with a given s, and let $s_q \equiv {}^{s}\!/\!_{p_q}$. 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. Hence, marginal productivity of capital, energy, and labor in production of good $q \in \{x, y\}$ are defined as MP_q^K, MP_q^E, and MP_q^L, respectively. Then, in order to derive factor prices uniquely, assume $\lim_{K\to 0} \mathrm{MP_q}^{\mathrm{K}} = \infty$ and $\lim_{K\to\infty} \mathrm{MP_q}^{\mathrm{K}} = 0$, and make similar assumptions about the marginal productivity of energy and labor.

Lemma 1: *(Inada conditions)* $\frac{MP_q^L}{MP_q^K}$ *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 (Lemma 1) imply that, given e_q and s_q, the optimal capital-labor ratios k_q are unique functions of $\omega \equiv \frac{w}{r}$ and are implicitly given by

$$\frac{MP_x^K}{MP_x^L}=\frac{\frac{\partial}{\partial k_x}\left(\widetilde{G}_x\left(k_x,e_x,s_q\right)\right)}{\left[\widetilde{G}_x\left(k_x,e_x,s_q\right)-k_x\cdot\frac{\partial}{\partial k_x}\left(\widetilde{G}_x\left(k_x,e_x,s_q\right)\right)-e_x\cdot\frac{\partial}{\partial e_x}\left(\widetilde{G}_x\left(k_x,e_x,s_q\right)\right)\right]}=\omega, \text{ and}$$

$$\frac{MP_y^K}{MP_y^L}=\frac{\frac{\partial}{\partial k_y}\left(\widetilde{G}_y\left(k_y,e_y,s_q\right)\right)}{\left[\widetilde{G}_y\left(k_y,e_y,s_q\right)-k_y\cdot\frac{\partial}{\partial k_y}\left(\widetilde{G}_y\left(k_y,e_y,s_q\right)\right)-e_y\cdot\frac{\partial}{\partial e_y}\left(\widetilde{G}_y\left(k_y,e_y,s_q\right)\right)\right]}=\omega. \tag{5}$$

In other words, the marginal rate of transformation equals ω. Similarly, given k_q and s_q, we can compute the optimal energy-labor ratio e_q, which is a unique function of $\upsilon \equiv \frac{w}{p_E}$.

Lemma 2: 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 rent to land s, determine ω and υ uniquely. To this end, let a_{jq} be the cost-minimizing amount of factor $j \in \{K, L, E, A\}$ used to produce one unit of good $q \in \{x, y\}$. The unit cost of sector q then equals $ra_{Kq} + wa_{Lq} + sa_{Aq} + p_E a_{Eq}$ (assuming land is allocated both to production and to the environment). Positive output and zero profits imply in equilibrium

$$\begin{aligned} p &= r\cdot a_{K,x} + w\cdot a_{L,x} + s\cdot a_{A,x} + p_E\cdot a_{E,x}, \text{ and} \\ 1 &= r\cdot a_{K,y} + w\cdot a_{L,y} + s\cdot a_{A,y} + p_E\cdot a_{E,y}. \end{aligned} \tag{6a}$$

Assume production of both fossil fuel and biofuel in equilibrium.[11] If production of fossil fuel is not at full capacity, i.e. $g_E^f\left(L_E{}^f, K_E^f\right) < \overline{E}^f$, then

[11] Note that, contrary to the assumptions made about sectors x and y, biofuel production may be zero. Hence, in equilibrium $p_E = r\cdot a_{K,E^f} + w\cdot a_{L,E^f}$ whereas $p_E < \Psi\cdot a_{A,E^b} + w\cdot a_{L,E^b}$.

$$r \cdot a_{K,E^f} + w \cdot a_{L,E^f} = p_E = s \cdot a_{A,E^b} + w \cdot a_{L,E^b} . \tag{6b}$$

If, on the other hand, the constraint is met, then $E^f = \overline{E}^f$ and Eq. (6b) becomes

$$\begin{aligned} &p_E \geq r \cdot a_{K,E^f} + w \cdot a_{L,E^f} \text{, and} \\ &p_E = s \cdot a_{T,E^b} + w \cdot a_{L,E^b} . \end{aligned} \tag{6b'}$$

Because the conversion cost of land is strictly positive and $\overline{L} - L_N > 0$, $s = \Psi$ in equilibrium. Pressure to change s is mitigated by a change in the amount of land allocated to production, $\overline{L} - L_N$. This result, namely that prices of factors and of non-traded goods are equalized among trading partners, may be viewed as a modification of the general theorem on factor price equalization as derived by Samuelson (1953). This extends Komiya (1967), which shows that if the number of internationally-traded goods is equal to or greater than the number of production factors among countries, both factor prices and the price of all goods, traded and non-traded, are equalized.

Proposition 1: *The relative price p and the conversion cost Ψ determine uniquely ω and υ. They also uniquely determine 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 1 and 2, given Eqs. (2) and (6).

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 and therefore is not affected by commodity prices.

Finally, given Ψ, we equate the relative supply of x in terms of y in H, $S_{x/y} \equiv \frac{x(.)}{y(.)}$, to the relative demand of x in terms of y, $D_{x/y}$, to derive the autarky price p. Using similar techniques, we can derive the autarky equilibrium in F.

4.1.2 The Energy Market

We now turn to the energy market, and depict the equilibrium level of energy produced from two alternative technologies, fossil fuel, E^f, and biofuel, E^b. We depict the demand and supply of energy in Fig. 1, where the "kink" in the supply function stems from the assumption that at low prices it is profitable to produce energy using fossil fuel, but it is not profitable to produce it using biofuel. We continue to concentrate on the equilibrium in which both biofuel and fossil fuel are produced, reflecting current market conditions.[12]

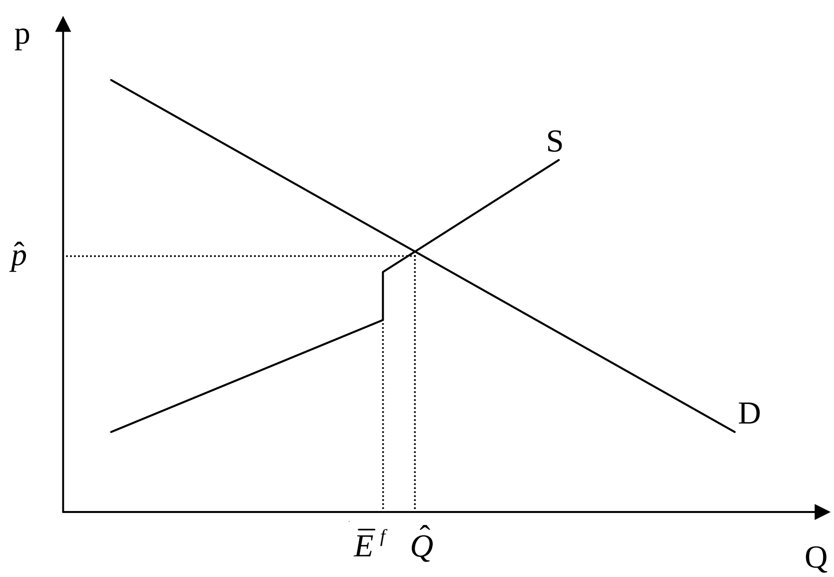

Fig. 1: The energy market

[12] Note that if the constraint on the quantity of energy produced using fossil fuel is binding and it is not profitable to produce energy using bio-fuel, we may witness quantity "stickiness", whereby, even though small changes in demand may increase prices, the quantity of energy supplied does not change. An exploration of the economics, policy, and history of biofuel in the U.S. can be found in Gardner (2007), Rajagopal (2007a and 2007b), among

4.2 The Trade Equilibrium where $\Psi = \Psi^*$

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

Assumption 2. $\frac{\bar{K}}{\bar{K}^*} > \frac{\bar{A}}{\bar{A}^*} > \frac{\bar{L}}{\bar{L}^*}$.

Rather than focusing on specific commodities, this paper derives the (indirect) trade flow of factor content, following work done on factor content of trade, which originated by the classic work of Vanek 1968.[13]

Proposition 2: *(Vanek 1968) Given Assumption 2 and* $\Psi = \Psi^*$, *Country H exports capital and imports labor. Furthermore, factor prices are equalized.*

Proof: The Proof is relegated to Appendix B.

From Proposition 2 we conclude that a country exports the service of the factor in which it is most abundant. We, however, cannot conclude 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).[14]

Proposition 3: *Given commodity prices, demand for energy increases when countries open to trade.*

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others.

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

[14] The chain version of the Heckscher-Ohlin theorem was first proposed by Jones (1956-1957), but Bhagwati shows that it is not true if factor prices are equalized. Deardroff (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.

Since firms maximize profits and technology is convex, it can be shown that GDP increases with trade.[15] 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; Globalization causes the demand for energy to increase.

4.3 The Trade Equilibrium where $\Psi \neq \Psi^*$

In reality, governments' preferences differ. Some governments place higher weight on the environment, and therefore place a higher value on land not used for production. Heterogeneity in conversion costs can be explained not only by rent-seeking activity but also by differences among countries in income distributions and land resources, which effect emission control. This section asks how such differences affect the trade equilibrium.

Proposition 4: *On average, given identical and constant-return-to-scale technologies and identical and homothetic preferences across countries and given Assumption 2, H exports capital, whereas F exports land and labor.*

Proposition 4 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. Therefore, given Assumption 2, F exports land services to H. Proposition 4 also follows from Staiger (1986), which shows that, on average, a country exports services of the abundant factor. This allows us to identify trade flow between two countries in terms of factor content. This implies

[15] 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.

the country that values the environment more is the country that imports land services. Since, the conversion cost is determined by the social planner and is set at a lower level in F, we can pin down, on average, the flow of factor content. In the traditional three factors two goods Heckscher-Ohlin trade model, where factor prices are determined by commodity prices and equalized across countries, such a prediction is not possible.

5. Capital Accumulation

The current section investigates how an increase in capital affects the free trade equilibrium. The Rybczynski effect is derived. In particular, borrowing the terminology of Jones and Scheinkman (1977), we argue that capital is a "friend" to capital goods and an "enemy" to food, in the sense that a rise in the amount of capital increases the amount of capital goods produced and reduces the amount of food produced. This result is shown while exploiting the full-employment conditions (Eq. (2)) to derive the Rypczynski effect, holding fixed the conversion cost of land.

Proposition 5: *(Rypczynski effect) Given p and* Ψ*, an increase in capital K increase the aggregate supply of y and* E^f*, while the aggregate supply of x decreases.*

Because commodity and factor prices are fixed, the capital-labor ratio is unchanged. The capital resource constraint, Eq. (2), then, equals

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

where a caret (^) above a variable denotes a proportional change. Hence, and given $\hat{k}_x < \min\left\{\hat{k}_E, \hat{k}_y\right\}$, $\frac{\partial L_y}{\partial \hat{K}} = \frac{1}{\hat{k}_y - \hat{k}_x} > 0$, and $\frac{\partial L_E}{\partial \hat{K}} = \frac{1}{\hat{k}_E - \hat{k}_x} > 0$. Then it can be shown, using Eq. (4), that

$$\frac{\partial y}{\partial \hat{K}} = \frac{\widetilde{G}_y\left(\hat{k}_y, \hat{e}_y, \Psi_y\right)}{\hat{k}_y - \hat{k}_x} > 0,$$

$$\frac{\partial E^f}{\partial \hat{K}} = \frac{\widetilde{G}_E\left(\hat{k}_E\right)}{\hat{k}_E - \hat{k}_x} > 0, \text{ and}$$

$$\frac{\partial x}{\partial \hat{K}} = \frac{-\left(\hat{k}_y - \hat{k}_x + \hat{k}_E - \hat{k}_x\right)\widetilde{G}_x\left(\hat{k}_x, \hat{e}_x, \Psi_x\right)}{\left(\hat{k}_y - \hat{k}_x\right)\left(\hat{k}_E - \hat{k}_x\right)} < 0,$$

which is the Rypczynski effect. Thus, capital goods and energy are "friends" of the factor capital, i.e., $\hat{K}_y > \hat{\bar{K}}$ and $\hat{K}_E > \hat{\bar{K}}$, and capital is an "enemy" of food, i.e., $\hat{K}_x < \hat{\bar{K}}$. This conclusion is consistent with empirical observation that shows an increase in FDI relative to domestic capital investment in countries like China and India (UNCTAD 2000) is accompanied by an increase in energy demand and a subsequent increase in the quantity of capital goods supplied.

Increasing $\bar{K}$ not only changes the pattern of production (as predicted by the Rybczynski effect), but also increases the amount of land allocated to production.

Proposition 6: *Given p and Ψ, increasing* $\bar{K}$ *increases the amount of land allocated to production, where the level of pollution Z increases.*

Let capital increase by the ratio $\frac{\bar{K} + \hat{K}}{\bar{K}}$. The marginal benefit from land increases, hence demand for land shifts up and to the right. Because commodity and factor prices are fixed, in equilibrium, $s/p = \Psi/p$ for all $\hat{K}$. Therefore, the increase in capital $\hat{K}$ should be supplemented by an increase in land $\hat{A}$. Furthermore, because demand for fossil fuel increases (Proposition 6) the level of pollution, Z increases.

Figure 2 summarizes this result. In particular, if land cannot be reallocated to production, then in equilibrium, rent from land in real terms should increase (point B in Fig. 2). If, on the other hand, land can be reallocated to production, then the equilibrium return to land in real terms is unchanged (point A in Fig. 2). This conclusion suggests a role for the government in setting the price of land Ψ.

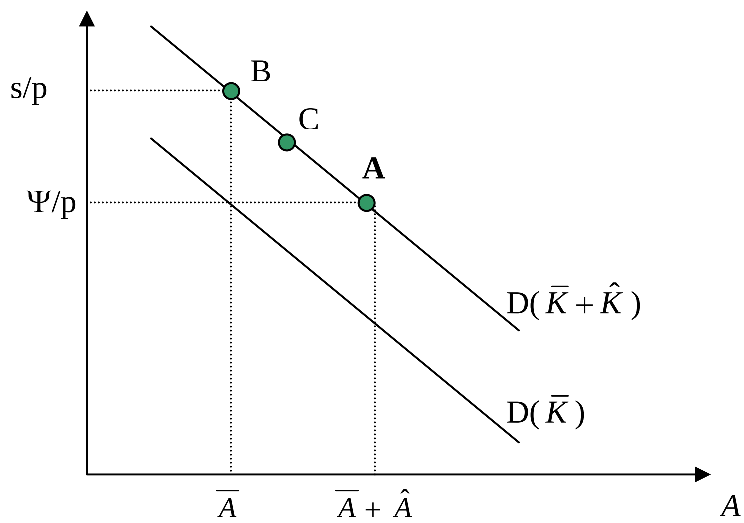

Fig. 2: Demand for land for production, following the increment in capital

Throughout this paper, we assume the conversion cost of land is constant. If one allows the conversion cost of land to equal the marginal benefit from land allocated to the environment and if the marginal benefit of land allocated to the environment is a decreasing function of land, then the equilibrium is depicted by point C in Fig. 2. Put differently, if $\Psi\left(\bar{A} - A_n\right) = \frac{\partial u_n}{\partial n} \times \frac{\partial g_n}{\partial A_n}$ then $\partial \Psi \big/ \partial\left(\bar{A} - A_n\right) > 0$. Furthermore, if $K_0<K_1$ then $A_0<A_1$, and therefore $\Psi\left(A_0\right) < \Psi\left(A_1\right)$. The higher is the supply elasticity of land allocated to production, the bigger is the impact of capital inflows on the economy's production activity (and the higher is the level of pollution in the economy).

6. Technical Changes

This section elaborates on technical changes, and how they affect prices, production and land allocation. More specifically, it focuses on *neutral technical* changes, where neutral technical changes shift upward the marginal product of all factors in the same proportion for all capital-labor and land-labor ratios.[16] Formally, the production function is of the form $\mu\tilde{G}(.)$, where μ denotes the technical-change parameter.

6.1 Technical changes in the capital 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

$$p = \mu_y \cdot \frac{\partial \widetilde{G_y}(.) / \partial k_y(.)}{\partial \widetilde{G}_x(.) / \partial k_x(.)} \text{ and } p = \mu_y \cdot \frac{\partial \widetilde{G_y}(.) / \partial e_y(.)}{\partial \widetilde{G}_x(.) / \partial e_x(.)}. \tag{12}$$

Let us define the capital-labor unit coefficient ratio of capital goods and food, the elasticity of supply of *q* with respect to *e* and *k*, and the marginal rate of transformation between energy and capital, respectively, as

[16] Since we wanted to focus on technical changes, while abstracting from biased growth, technical changes are assumed to be neutral.

$$s_k^{yx} \equiv \frac{k_y}{k_x},$$

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

$$TRS_{ke}^{q} \equiv \frac{\frac{\partial \widetilde{G}_q(.)}{\partial k_q}}{\frac{\partial \widetilde{G}_q(.)}{\partial e_q}} > 0,$$

for $q \in \{\xi, \psi\}$. Let us further define

$$MTRS_{ke}^{q} \equiv \frac{\frac{\partial^2 \widetilde{G}_q(.)}{\partial e_q \partial k_q}}{\frac{\partial^2 \widetilde{G}_q(.)}{\partial k_q^{\,2}}} \le 0 \text{ if } \frac{\partial^2 \widetilde{G}_q(.)}{\partial e_q \partial k_q} \ge 0 \left(\frac{\frac{\partial^2 \widetilde{G}_q(.)}{\partial e_q \partial k_q}}{\frac{\partial^2 \widetilde{G}_q(.)}{\partial k_q^{\,2}}} > 0 \text{ if } \frac{\partial^2 \widetilde{G}_q(.)}{\partial e_q \partial k_q} < 0 \right).$$

Given these definitions and Eq. (12), the following relation between technical changes and factor prices can be derived.

Proposition 7: *Given p and Ψ, if* $s_k^{yx} < \frac{\left(\eta_{xe}\left(1 - TRS_{ke}^{x} \cdot MTRS_{ke}^{x}\right) - 1\right)}{\left(\eta_{ye}\left(1 - TRS_{ke}^{y} \cdot MTRS_{ke}^{y}\right) - 1\right)} \frac{\eta_{yk}}{\eta_{xk}}$ *(henceforth denoted Condition 1) then* $\frac{\partial \omega}{\partial \mu_y} < 0$.

Proof: The proof is relegated to Appendix B.

Proposition 8 tells us that a necessary condition for real wage ω to decline with technical changes in the capital good sector μ_y is that η_{xk} and η_{ye} are sufficiently small relative to η_{xe} and η_{yk}. Condition 1 essentially requires food production to be more concave than capital-goods production in order for the real wage to decline with technical changes.

Next, given Proposition 7, we illustrate that not only do wages decrease with neutral technical changes in production of capital goods, but also the labor-output ratio declines. Proposition 7 links technical changes to the real wage, whereas Proposition 8 links changes in the real wage to production of food, *x*, and capital goods, *y*.

Proposition 8: *Assume a neutral technical change in the production of capital goods and fix p and Ψ. Then, if*

$$k_x < \min\{k_E, k_y\} \text{ and } 0 < \partial k_x / \partial \omega < \partial k_E / \partial \omega < \partial k_y / \partial \omega ,$$

y increases and x decreases when ω *decreases. In addition, the labor output coefficients,* a_{Kq}*, declines.*

Proof: The Proof is relegated to Appendix B.

Given neutral technical changes in production of capital goods and given Proposition 7, in the new equilibrium real wages decline and quantity of food decreases. Additionally, and given Assumption 2, F's terms of trade improve whereas H's terms of trade deteriorate (remember that on average H exports capital and imports labor).

6.2. Technical changes in the biofuel industry

Next, assume neutral technical changes in production of biofuel.

Proposition 9*: Given a neutral technical change in production of biofuel,* $\frac{y}{x}$ *increases and the price of food increases.*

To derive Proposition 9, fix prices and assume technical changes in the production of biofuel. These changes imply a higher return to labor used to produce biofuel (the marginal productivity of labor in biofuel denoted MP_L^b in Fig. 3 shifts up and to the left to $MP_L^{b'}$). Technical change in biofuel also increases the marginal productivity of land in biofuel. Then, given fixed conversion cost of land, the amount of land allocated for production of biofuel increases (we observe a horizontal shift, as depicted in Fig. 3). The cheaper supply of energy leads more firms to produce capital goods, and move away from the food sector. In the new equilibrium, the price of food increases whereas the supply of food decreases.

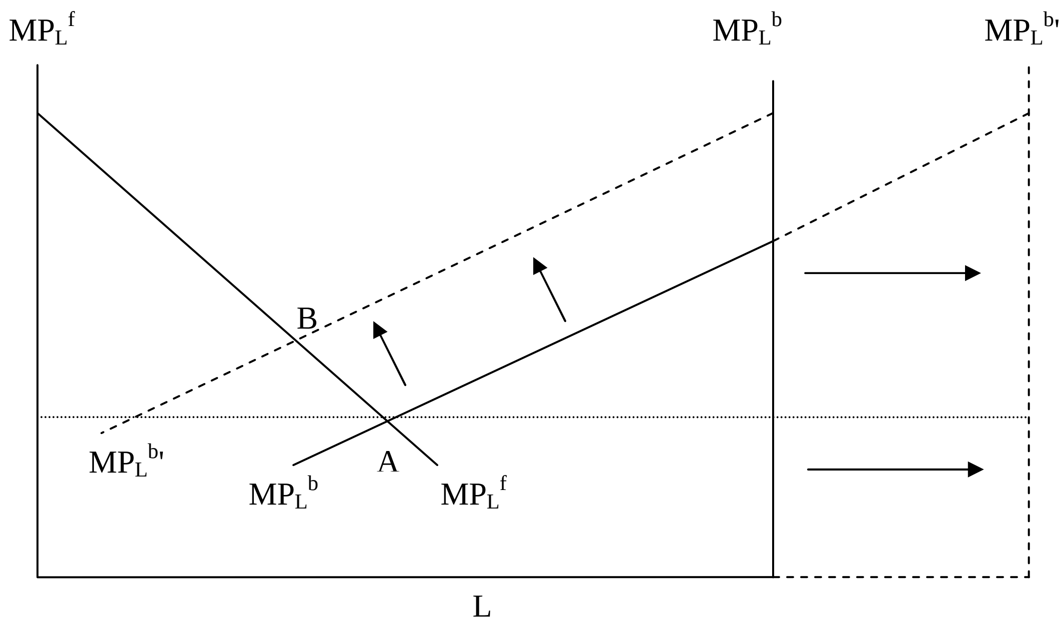

Fig. 3: Neutral technical changes in production of bio-fuel

The second generation of biofuel, as opposed to the first generation, aims to make biofuel production less land intensive and more efficient by relying on improved feedstocks such as cellulosic crops. The second generation, therefore, may *reduce* the demand for land. These technical changes, however, are not neutral, since they are targeted (partly) to reduce biofuel's dependence on land.

6.3. Technical changes in the food sector

Now, we assume technical changes in production of food, where the equilibrium conditions (Eq.

(12)) become

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

Technical changes in the food sector mirror technical changes in production of capital goods.

Proposition 10: *Given a neutral technical change in production of food,* $\mu_x, \frac{\partial \omega}{\partial \mu_x} > 0$.

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*

1. *x increases and y decreases, and*
2. *the labor output coefficients,* a_{Lq}*, declines.*

Recall neutral technical changes in capital goods reduce food production and increase food prices if Condition 1 holds. Remember also that Condition 1 holds if food production is more concave than capital goods production. To mitigate the tension between the energy sector and the food sector, then, we seek technical changes in food production that make food production less concave.

Since the mid-1990s, agricultural biotechnology 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, rice, and, notably, corn, increases yield per acre while also reducing pesticide applications (Zilberman and Qaim, 2003; Huang et al. 2002; Qaim and de Janvry, 2005; Traxler, 2001; Thirtle, 2003). The productivity gains provided by this technology lessen the loss of land allocated to food production and the environment. Agricultural biotechnology in food production can, therefore, represent a complimentary technology whose adoption alongside biofuel technology is consistent with goals of increasing renewable fuel production and reducing environmental damage.

7. Pollution Tax

Before concluding, and because the paper is addressing an environmental issue, a pollution tax is added. Governments decide whether or not to open up to trade and at what price to tax the pollution externality. By levying a pollution tax equal to the social cost of pollution, governments internalize the externality. We illustrate that, although a pollution tax does not qualitatively affect the results of the foregoing analysis, it does increase the incentives to substitute fossil fuel with biofuels. This is consistent with the coordinated effort of some countries to reduce the pollution externality and spur biofuel production and suggests the two policies are complimentary.

Formally, the pollution tax equals the marginal social cost of fossil fuel combustion. A pollution tax decreases the price received by producers using fossil fuel. The decline in producer's price causes the supply of energy from extracting fossil fuel to contract, leading to an increase in the price of energy. The increase in the price of energy triggers an increase in the return to land used to grow biofuel crops; an increase that leads the amount of land allocated to biofuels to increase .

Proposition 11: *A pollution tax increases production of energy using biofuels, and decreases production of energy using fossil fuel .*

A pollution tax leads to substitution of fossil fuel with biofuel. It, therefore, increases the tension between food production, the environment and biofuel, and causes the energy market to seek alternative ways of extracting energy. Proposition 11 highlights an important drawback of carbon taxes: Although a pollution tax reduces greenhouse gases from fossil fuel, it comes at the price of deforestation and biodiversity loss, as well as lost food production. Because the agricultural sector contributes significantly to the portfolio of policy measures to combat global warming (e.g., Houghton 2003, and Van Der Werf and Peterson 2007), and forests also play an important role in climate change, the benefits from pollution taxes are minimized by changes in land use.

8. Discussion and Concluding Remarks

This work introduces a ubiquitous input, energy, and the environment to a standard Heckscher-Ohlin trade model. By extending traditional trade models to incorporate energy and the environment, we develop a framework to explore the economics of biofuel. Biofuel production is land intensive, particularly compared to oil production. Therefore, adopting biofuel technology has attendant consequences for food production and environmental preservation, the two predominant uses of land today. Furthermore, energy is a ubiquitous good used by both producers and consumers. It is a homogeneous input used at all stages of production, including the “production” of utility from physical goods. These consequences should not be ignored in determining the welfare effects of biofuels and globalization.

Globalization increases the production possibilities and introduces an indirect (albeit efficient) method of production. In doing so, it increases production and creates new demand for energy. The increase in demand for energy, given the constraint on the amount of fossil fuel produced and the cost of producing biofuel, increases energy prices. Globalization also creates new demand for land for production, thus leading to deforestation. Demand for energy also increases with capital accumulation, which increases the amount of capital goods produced and capital services consumed. These trends also come at the expense of food production and biodiversity. This paper, therefore, points to the cost of globalization and capital flows and their consequences for food supplies and the environment.

These conclusions are consistent with empirical observation of global capital and energy markets. For instance, FDI, along with government investment, have liftted overall investment in China, contributing to China's growth. This growth led to a sharp increase in demand for energy, and forced China to become a major importer of oil. Similar changes in demand for energy can also be documented in India, among other places. These global changes were followed by changes in oil prices, which recently reached new nominal highs that may have eclipsed the all-time highs of the early 1980s. Finally, leading newspapers around the world have documented the rising price of corn, which has caused an increase in the price of food commodities, including livestock, dairy and sweeteners.

The tension 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 three 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 increase demand for energy and thereby increase demand for land for energy production. This reduces the allocation of land to food and environmental 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, they also increase biofuel production, which generates higher demand for land in biofuel. Agricultural 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 innovations in food production can also alleviate the land constraint and attenuate the impacts of biofuel adoption on food supply and land allocations.

Appendix A

Producers minimize the cost of production and are price takers. Their problem can be described as follows:

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

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

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

As defined in Section 3, $s_q = \frac{s}{p_q}$ is the real rent of land in terms of good q and

$$G_q\left(L_q, K_q, E_q, s_q\right) \equiv \max_{A_q} \left\{ p_q \cdot g_q\left(L_q, A_q, K_q, E_q\right) - s \cdot A_q \right\}. \qquad \text{(1B)}$$

The solution to (1B) 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. 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. (5), can be rewritten as

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

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

Appendix B

Proof of Proposition 2

We start by deriving the comparative advantage of the countries, given equal factor prices. First, note that equalization of commodity prices under free trade, given our assumption that preferences are identical and homothetic across countries, implies that countries spend the same share of their income on each commodity, and in particular,

$$x = \alpha x^*,\ \mathrm{y}=\alpha y^*, \text{ and } \mathrm{c}=\alpha c^*,$$

where α is the ratio between country H's consumption of good *i* and country F's consumption of the good under free trade. The value of α depends on free trade prices.

Next, we express goods consumed and produced in terms of their factor content.[17] According to this result, known as the Heckscher-Ohlin-Vanek Theorem, countries are net exporters of the services of their abundant factors and net importers of the services of their scarce factors, embodied as factor content in the goods they trade.

Country H's consumption demand for factor *j* under free trade is equal to

$$v_j^{\mathrm{C}} = \mathrm{a}_{\mathrm{xj}}\mathrm{x} + \mathrm{a}_{\mathrm{yj}}\mathrm{y} + \mathrm{a}_{\mathrm{cj}}\mathrm{c},$$

where a_{ij} is the input-output coefficient for good *i* evaluated at free-trade factor prices and is the same in both countries because of identical technologies and factor price equalization. Then, we define the net export of services of factor *j* by country H as

$$v_j^{\mathrm{E}} \equiv v_j - v_j^{\mathrm{C}} = \frac{v_j - \alpha \cdot v_j^*}{1+\alpha}, \tag{10}$$

where v_j denotes factor *j*'s endowment in H, and v_j^* denotes factor *j*'s endowment in F.

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

The following result, which follows from Eq. (10), is attributed to Vanek (1968):

$$v_j^{\mathrm{E}} \begin{Bmatrix} > \\ = \\ < \end{Bmatrix} 0 \text{ if and only if } \frac{v_j}{v_j^*} \begin{Bmatrix} > \\ = \\ < \end{Bmatrix} \alpha. \tag{11}$$

This result implies that a country exports the service of the most abundant factor. Furthermore, if a country exports a factor, it must also export all factors that are abundant in that country. Therefore, and given the existence of trade, country H exports capital and imports labor.

To show that factor prices are equalized, note that factor prices, as well as the allocation of resources, are determined once p and Ψ are set. Then, since (i) $\Psi=\Psi^*$, (ii) preferences and technology are the same in both countries, (iii) factor endowments are similar for the two countries, and (iv) there are no trade impediments (e.g., tariffs and transportation costs), $p=p^*$ and, therefore, factor prices are equalized.

Proof of Proposition 7:

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

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

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

Bradford, and Shimpo (1997) and Davis and Weinstein (1996).

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

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

$$\frac{\partial k_x}{\partial \omega}=\left[\frac{\left(e_x\left(\dfrac{\partial \widetilde{G}_x(.)}{\partial e_x}\dfrac{\partial^2 \widetilde{G}_x(.)}{\partial {k_x}^2}-\dfrac{\partial^2 \widetilde{G}_x(.)}{\partial e_x \partial k_x}\dfrac{\partial \widetilde{G}_x(.)}{\partial k_x}\right)-\widetilde{G}_x(.)\dfrac{\partial^2 \widetilde{G}_x(.)}{\partial {k_x}^2}\right)}{\left(\dfrac{\partial \widetilde{G}_x(.)}{\partial k_x}\right)^2}\right]^{-1} \text{ and}$$

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

Then,

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

$$\frac{\dfrac{\partial^2 \widetilde{G}_x(.)}{\partial {k_x}^2}\dfrac{\partial k_x}{\partial \omega}}{\dfrac{\partial \widetilde{G}_x(.)}{\partial k_x}}<\frac{\dfrac{\partial^2 \widetilde{G}_y(.)}{\partial {k_y}^2}\dfrac{\partial k_y}{\partial \omega}}{\dfrac{\partial \widetilde{G}_y(.)}{\partial k_y}}$$

Hence, as

$$\frac{\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2}\frac{\partial k_x}{\partial \omega}}{\frac{\partial \widetilde{G}_x(\cdot)}{\partial k_x}} < \frac{\frac{\partial^2 \widetilde{G}_y(\cdot)}{\partial k_y{}^2}\frac{\partial k_y}{\partial \omega}}{\frac{\partial \widetilde{G}_y(\cdot)}{\partial k_y}} \Leftrightarrow$$

$$\frac{\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2}\frac{\partial \widetilde{G}_x(\cdot)}{\partial k_x}}{\left(e_x\left(\frac{\partial \widetilde{G}_x(\cdot)}{\partial e_x}\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2} - \frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial e_x \partial k_x}\frac{\partial \widetilde{G}_x(\cdot)}{\partial k_x}\right) - \widetilde{G}_x(\cdot)\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2}\right)} <$$

$$\frac{\frac{\partial^2 \widetilde{G}_y(\cdot)}{\partial k_y{}^2}\frac{\partial \widetilde{G}_y(\cdot)}{\partial k_y}}{\left(e_y\left(\frac{\partial \widetilde{G}_y(\cdot)}{\partial e_y}\frac{\partial^2 \widetilde{G}_y(\cdot)}{\partial k_y{}^2} - \frac{\partial^2 \widetilde{G}_y(\cdot)}{\partial e_y \partial k_y}\frac{\partial \widetilde{G}_y(\cdot)}{\partial k_y}\right) - \widetilde{G}_y(\cdot)\frac{\partial^2 \widetilde{G}_y(\cdot)}{\partial k_y{}^2}\right)}$$

where

$$\frac{\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2}\frac{\partial \widetilde{G}_x(\cdot)}{\partial k_x}}{\left(e_x\frac{\partial \widetilde{G}_x(\cdot)}{\partial e_x}\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2} - \widetilde{G}_x(\cdot)\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2} - e_x\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial e_x \partial k_x}\frac{\partial \widetilde{G}_x(\cdot)}{\partial k_x}\right)}$$

$$= \frac{\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2}\frac{\partial \widetilde{G}_x(\cdot)}{\partial k_x}\frac{1}{\widetilde{G}_x(\cdot)}}{\left(\frac{e_x}{\widetilde{G}_x(\cdot)}\frac{\partial \widetilde{G}_x(\cdot)}{\partial e_x}\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2} - \frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2} - \frac{e_x}{\widetilde{G}_x(\cdot)}\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial e_x \partial k_x}\frac{\partial \widetilde{G}_x(\cdot)}{\partial k_x}\right)}$$

$$= \frac{\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2}\frac{\partial \widetilde{G}_x(\cdot)}{\partial k_x}\frac{k_x}{\widetilde{G}_x(\cdot)}\frac{1}{k_x}}{\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2}\left(\frac{e_x}{\widetilde{G}_x(\cdot)}\frac{\partial \widetilde{G}_x(\cdot)}{\partial e_x} - 1 - \frac{e_x}{\widetilde{G}_x(\cdot)}\frac{\partial \widetilde{G}_x(\cdot)}{\partial e_x}\frac{\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial e_x \partial k_x}}{\frac{\partial^2 \widetilde{G}_x(\cdot)}{\partial k_x{}^2}}\frac{\frac{\partial \widetilde{G}_x(\cdot)}{\partial k_x}}{\frac{\partial \widetilde{G}_x(\cdot)}{\partial e_x}}\right)}$$

$$= \frac{\eta_{xk}\frac{1}{k_x}}{\left(\eta_{xe}\left(1 - TRS_{ke}^{x} \cdot MTRS_{ke}^{x}\right) - 1\right)}$$

and

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

we get

$$\frac{\partial \omega}{\partial \mu_y}<0 \Leftrightarrow \frac{\eta_{xk}\frac{1}{k_x}}{\left(\eta_{xe}\left(1-TRS_{ke}^{x}\cdot MTRS_{ke}^{x}\right)-1\right)}<\frac{\eta_{yk}\frac{1}{k_y}}{\left(\eta_{ye}\left(1-TRS_{ke}^{y}\cdot MTRS_{ke}^{y}\right)-1\right)}$$
$$\Leftrightarrow s_k^{yx}<\frac{\left(\eta_{xe}\left(1-TRS_{ke}^{x}\cdot MTRS_{ke}^{x}\right)-1\right)}{\left(\eta_{ye}\left(1-TRS_{ke}^{y}\cdot MTRS_{ke}^{y}\right)-1\right)}\frac{\eta_{yk}}{\eta_{xk}}$$

Proposition 7 follows.

Q.E.D.

Proof of Proposition 8:

To derive this result, we follow techniques developed by Jones (1965). Specifically, we exploit the conditions $\frac{\partial c^i(.)}{\partial w}=\mu_i a_{Li}$, while using the assumption that the unit cost functions are linear homogeneous in their arguments (i.e., $0=w\frac{\partial^2 c^i}{\partial w^2}+r\frac{\partial^2 c^i}{\partial w \partial r}+s\frac{\partial^2 c^i}{\partial w \partial s}$), to derive the following conditions:

$$\hat{a}_{Li}=-\Theta_{Ki}\sigma_i^{wr}\left(\hat{w}-\hat{r}\right)-\Theta_{Ai}\sigma_i^{ws}\left(\hat{w}-\hat{s}\right)-\hat{\mu}_i,$$
$$\hat{a}_{Ki}=\Theta_{Li}\sigma_i^{wr}\left(\hat{w}-\hat{r}\right)-\Theta_{Ai}\sigma_i^{rs}\left(\hat{r}-\hat{s}\right)-\hat{\mu}_i, \text{ and}$$
$$\hat{a}_{Ai}=\Theta_{Li}\sigma_i^{ws}\left(\hat{w}-\hat{s}\right)+\Theta_{Ki}\sigma_i^{rs}\left(\hat{r}-\hat{s}\right)-\hat{\mu}_i,$$

where the elasticity of substitution between factor h and j in sector i is denoted $\sigma_i^{hj}=\frac{c_i(.)\frac{\partial^2 c_i(.)}{\partial r \partial w}}{\frac{\partial c_i(.)}{\partial w}\frac{\partial c_i(.)}{\partial r}}$ and Θ_{ji} denote the cost shares of input j in sector i (e.g., $\Theta_{ji}\equiv\frac{ra_{Ki}}{p_i}$). Note also that since the government set Ψ, and in equilibrium Ψ=s, $\hat{s} = 0$. Now, while using Proposition 7, we can show that neutral technical changes cause the capital-output ratio to decline, i.e., $\hat{a}_{Ki} < 0$.

Next, we exploit the full-employment conditions to derive *x* and *y*, i.e.,

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

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

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

because $k_x < \min\left\{k_E, k_y\right\}$ 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 (Proposition 8). Therefore, given neutral technical changes in the production of capital, *x* declines and *y* increases.

Q.E.D.

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