



***The Economics of Trade, Biofuels and the Environment***

by

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Paper presented at the  
International Agricultural Trade Research Consortium  
Annual Meeting Theme Day

December 7-9, 2008  
Scottsdale, Arizona

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November 21, 2008

## Abstract

This work extends traditional trade models to consider energy and the environment by introducing energy as ubiquitous (intermediate) input, using a household model where energy enters directly into consumer decisions, and assuming externalities related to land and energy consumption. Under plausible conditions, globalization and capital flows increase demand for energy, leading to decline in food production and loss of environmental land. Identical technologies and similar resource constraints across countries are not sufficient for factor price equalization. Although the social optimal policy includes a land tax and an emission tax, under certain conditions the use of only one instrument may be worse to the environment, in contrast to no intervention at all. Furthermore, technological changes, e.g., agriculture biotechnology and second generation biofuels, are shown to lessen the land constraint.

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

*JEL Code:* D1, F1, Q4

## 1 Introduction

Whereas non-renewable, non-recyclable petroleum was a primary source of transportation fuel around the world for most of the 20<sup>th</sup> century, a number of economic and social trends seem to suggest a new energy paradigms for much of the 21<sup>st</sup> century. These new paradigms are driven by increasingly costly oil, heightened concern about the environment and climate change, and rising demand for

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<sup>†</sup>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.

energy, principally in rapidly growing Asian countries integrated to the global trade system.<sup>1</sup> 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.<sup>2</sup> 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 (a la Lancaster 1966 and 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, an environmental amenity (henceforth, the environment), and a characteristic called convenience, which is produced within the household in a production function that combines manufactured goods and energy.<sup>3</sup> Because households are responsible for a significant share of energy demand,<sup>4,5</sup> 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. On the other hand, the environment is increasing in land allocated to the environment, a public good with both local and global ramifications, and decreasing in greenhouse gas emissions, a global public bad.<sup>6</sup> For the sake of simplicity, food commodities equals physical food purchased.

We employ the Heckscher-Ohlin model as a clear and simple way to introduce household production in a general equilibrium trade framework, and therefore explicitly introducing the household model to the trade literature. We assume a two-country model, with identical constant return 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.<sup>7</sup> Both countries may use land taxes and emissions taxes to internalize externalities

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

<sup>2</sup>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 wind or solar, not bioenergy.

<sup>3</sup>This work extends Becker 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 tradeoff. Energy is introduced as a homogeneous good affecting all stages of production and consumption.

<sup>4</sup>A conservative estimate 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. 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 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.

<sup>5</sup>Vandenbergh and Steinemann (2007).

<sup>6</sup>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.

<sup>7</sup>The economic structure builds on work (originated by Samuelson (1953), and extended by Melvin (1968), Drabicki

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 2008), as well as the trade-off between energy and food. Although the biofuel industry is prone to periods of boom and bust driven by food market volatility (Hochman et al. 2008), we assume throughout the paper a deterministic setup, and that biofuel production is profitable under certain conditions. 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 a 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 acceleration in the transition to a service economy in many non-OECD countries).

Technical changes in agriculture and biased technical changes in biofuel production (that reduce land intensity) are shown to lessen the land constraint and thereby reduce losses of natural land and upward pressure on food prices. We illustrate that the use of only one policy instrument may be worse to the environment, in contrast to no intervention. If land tax is set sub-optimally low then an emissions tax will trade emission reductions for expansion of productive land relative to the social optimum. A sub-optimal land tax in Brazil, e.g., no land tax, suggests land (which used to be allocated to rain forests) is over utilized whereas fossil fuel is underutilized, in contrast to the social optimum solution. Environmental policy instrument and 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, and changes in capital considered. Sections 4 considers changes in technology. Section 5 models the effects of suboptimal policy. Section 6 discusses results and concludes.

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and Takayama (1979), Dixit and Norman (1980), Deardorff (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). 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 environmental,  $n$ , and food,  $x$ .<sup>8</sup> As in Becker, commodities are concrete and physical. However, we assume activity combines energy and manufactured goods and transform them into convenience.

Convenience characteristics supply the household with convenience 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 is denoted by  $n \equiv g_n(A_n, Z)$ , where  $A_n$  is natural land and  $Z$  is emissions of greenhouse gases. 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

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<sup>8</sup>Note that land for environment has use benefits (including, recreation, environmental services, etc.) and non-use benefits (including biodiversity, option value, bequest value, etc.).

$$U = u_x(x) + u_y(c) + u_n(n). \quad (1)$$

Sub-utility  $u_x(x)$  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  $u_n(n)$ . 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 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

$$p_x \cdot x + p_c \cdot c \leq I, \quad (2)$$

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  $i$ ; i.e.,

$$c_c(p_E) = \min_{\{a_{j_c}\}_{j \in \{y, E\}}} \{a_{y_c} + p_E \cdot a_{E_c} : g_c(a_{y_c}, a_{E_c}) \geq 1\}. \quad (3)$$

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. Then they maximize their utility subject to their budget constraint.<sup>9</sup>

## 2.2 Technology

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

$$E^f = g_E^f(L_E^f, K_E^f) \text{ and } E^b = g_E^b(L_E^b, A_E^b). \quad (4)$$

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.<sup>10</sup>

In the United States, biofuel policy includes production tax credits that have historically been used to help biofuels compete with cheaper-to-produce gasoline. With gasoline prices reaching nominal

<sup>9</sup>We assume that the conditions required for two step maximization hold (See Green 1964).

<sup>10</sup>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.

highs at retail stations and even real records not seen since the 1970s 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 sugar cane to ethanol are cost competitive with gasoline but also corn ethanol; at 100 USD a barrel many biofuel crops are efficient without government support. Therefore, and although subsidizing biofuel does distort production decisions (Gardner and Tyner 2007; Tyner and Taheripour 2007; among others), we elected to concentrate throughout this paper on a generic equilibrium with no subsidies in which both biofuel and fossil fuel are produced. To extend traditional general equilibrium trade model to include energy and environmental considerations and derive the optimal solution.<sup>11</sup>

We depict the demand  $D$  and supply  $S$  of energy in Fig. 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  $p_0$ . To this end, Tyner and Taheripour (2007) used US 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.

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

$$x = g_x(L_x, K_x, A_x, E_x) \quad \text{and} \quad y = g_y(L_y, K_y, A_y, E_y). \quad (5)$$

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

$$\begin{aligned} \bar{K} &= K_E + K_x + K_y, \\ \bar{L} &= L_E + L_x + L_y, \text{ and} \\ \bar{A} &= A_E + A_x + A_y + A_n. \end{aligned} \quad (6)$$

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

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<sup>11</sup>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 De-Gorter and Just (2008), Gardner (2007), Hochman et al. (2008), Rajagopal (2007), among others.

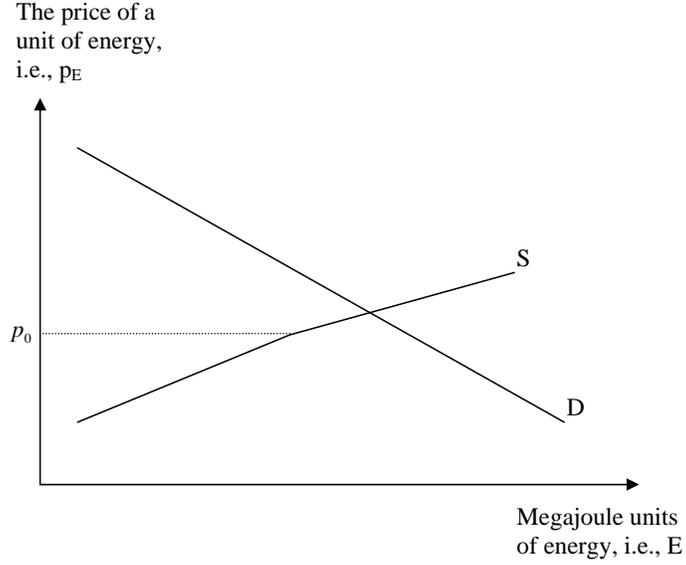


Figure 1: The energy market

energy. Reallocating land to production releases the carbon captured in the natural land and produces carbon emissions. We therefore assume the “emissions function” is  $Z \equiv g_Z(E_p, A_p)$ , 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  $E_p \equiv E^f + E^{*f} + \rho(E^b + E^{*b})$  and  $A_p \equiv \bar{A} - A_n + \bar{A}^* - A_n^*$ . Although emissions related to the inputs used in production of biofuel could decrease or increase greenhouse gas emissions relative to its fossil substitute, i.e., crude oil (Farrell et al., 2006; Rajagopal and Zilberman 2008; among others), in what follows, and to simplify the presentation, we assume  $\rho < 1$ . Although biofuel may increase or decrease Greenhouse Gas emissions relative to the average technology used to extract fossil fuel, i.e., crude oil, under plausible scenarios biofuel produced from corn starch (currently, the “dirtiest” biofuel feedstock) emits less Greenhouse Gas emissions than the marginal technology used to extract fossil fuel (e.g., Tar Sand) – Hochman et al. (2008b).

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

In other words, 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

$$c_q(w, s, r, p_E) = \min_{\{a_{Lq}, a_{Aq}, a_{Kq}, a_{Eq}\}} \{w \cdot a_{Lq} + s \cdot a_{Aq} + r \cdot a_{Kq} + p_E \cdot a_{Eq} : g_q(a_{Lq}, a_{Aq}, a_{Kq}, a_{Eq}) \geq 1\} \quad (7)$$

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

$$\frac{\partial a_{Lq}}{\partial w} \leq 0, \frac{\partial a_{Aq}}{\partial s} \leq 0, \frac{\partial a_{Kq}}{\partial r} \leq 0, \text{ and } \frac{\partial a_{Eq}}{\partial p_E} \leq 0. \quad (8)$$

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.

### 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 and global ramifications. Consumption of fossil fuel causes carbon emissions, a global public bad. 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. 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 work toward this goal in two steps: First, assuming land is allocated to maximize firm profits, we can rewrite the production functions of  $x$  and  $y$  as a function of capital, land, energy, and real land tax only.<sup>12</sup> We

<sup>12</sup>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).

apply these techniques, given that land can be used either for production or for nature. 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 extend to a big economy.

### 3.1 The Trade Equilibrium: A small open economy

In Appendix A, the Stolper-Samuelson theorem, as derived by Samuelson (1953), is modified. Specifically, and different from the standard trade models, prices of factors 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.<sup>13</sup>

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

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

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

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

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  $v \equiv \frac{w}{s}$ . 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  $\lim_{i \rightarrow 0} MP_q^i = \infty$  and  $\lim_{i \rightarrow \infty} MP_q^i = 0$ . These are the *Inada Conditions*.

**Lemma 1** *Given the Inada Conditions, the relative price  $p$ , the land tax  $\Psi$ , and the carbon tax  $\Phi$  determine uniquely  $s$ ,  $\omega$ , and  $v$ . 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., Eq. (2), and the zero-profit condition. See Appendix A.

<sup>13</sup>The paper, therefore, also extends 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.

The government sets the land tax equal to the marginal benefit from natural land, i.e.,  $\Psi = \frac{\partial u_n}{\partial n} \times \frac{\partial g_n}{\partial A_n}$ , which does not include emissions from reallocating land to production, i.e.,  $\frac{\partial g_n}{\partial Z} \times \frac{\partial qz}{\partial A_n}$ . The government also set a carbon tax equal to the global marginal cost of emissions, i.e.,  $\Phi = -\frac{\partial u_n}{\partial n} \times \frac{\partial g_n}{\partial Z}$ . For each unit of carbon produced by combustion of fossil fuel and biofuel, consumers pay. In addition, emissions from converting natural land to production are taxed, i.e., tax on indirect emissions equals  $\Phi \times \frac{\partial qz}{\partial A_n}$ .<sup>14</sup> Let  $p_L$  denote the price of land. 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.

**Lemma 2** *The price of land increases in emissions and in land reallocated to production, i.e.,  $p_L = \Psi + \Phi \times \frac{\partial qz}{\partial A_n}$ .*

In equilibrium, and because all markets are competitive,

$$p \cdot MP_E^x = p_E = MP_E^y \text{ and } p \cdot MP_A^x = p_L = MP_A^y \quad (9)$$

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.,  $\Phi \cdot \frac{\partial qz}{\partial E^f}$ , 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.,  $\Phi \cdot \rho \cdot \frac{\partial qz}{\partial E^b}$ .

An alternative tax, which is implemented today in many countries, is a fuel tax. In the paper, the optimal fuel tax equals the marginal cost of carbon emissions associated with consumption of fuel, i.e.,  $\Phi \times \frac{\partial qz}{\partial E^p}$ . 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 land owners not to use their land. By paying  $p_L$  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. In allocating  $A_n$  units of land to the environment or allocating permits to utilize  $\bar{A} - A_n$  units of land, the regulator achieves optimal resource allocations. Though these instruments may all achieve the socially optimal allocations, instruments have different implications for distribution of total surplus.<sup>15</sup>

### 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

<sup>14</sup>Although life cycle analysis suggests biofuel are not carbon neutral, in the paper we focus only on indirect emissions. As pointed above, introducing direct emissions does not change the paper's results, as long as biofuel is less polluting than fossil fuel.

<sup>15</sup>See Cropper and Oates (1992).

and an "enemy" to food. Put differently, an increase in capital boosts the amount of manufactured goods produced and reduces the amount of food produced; namely, the Rypczynski effect. This result is shown while exploiting the full-employment conditions (Eq. (6)). Increasing  $\bar{K}$  not only changes the pattern of production (as predicted by the Rypczynski effect), but also increases the amount of land allocated to production.

**Proposition 1** *Increasing capital  $\bar{K}$  increases the amount of land allocated to production 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; indirect emissions from biofuel production increases. Therefore, the increase in capital  $\Delta K$  should be supplemented by an increase in land  $\Delta A$  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  $D^{-1}(\cdot)$ . If  $\bar{K}_0 < \bar{K}_1$  then  $A_{n,0} \geq A_{n,1}$  ( $A_{p,0} \leq A_{p,1}$ ), and therefore  $p_{L,0} < p_{L,1}$ . 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 FDI relative to domestic capital investment in countries like China and India is accompanied by an increase in energy demand and a subsequent increase in the quantity of manufacture goods supplied (UNCTAD 2000)<sup>16</sup>.

### 3.2 The trade equilibrium: A big open economy

We now show that although trade may equalize prices of traded goods, identical prices of traded goods across countries are not a sufficient condition 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

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

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<sup>16</sup>World Investment Report 2000: Cross-border Mergers and Acquisitions and Development, United Nations Conference on Trade and Development, 2000

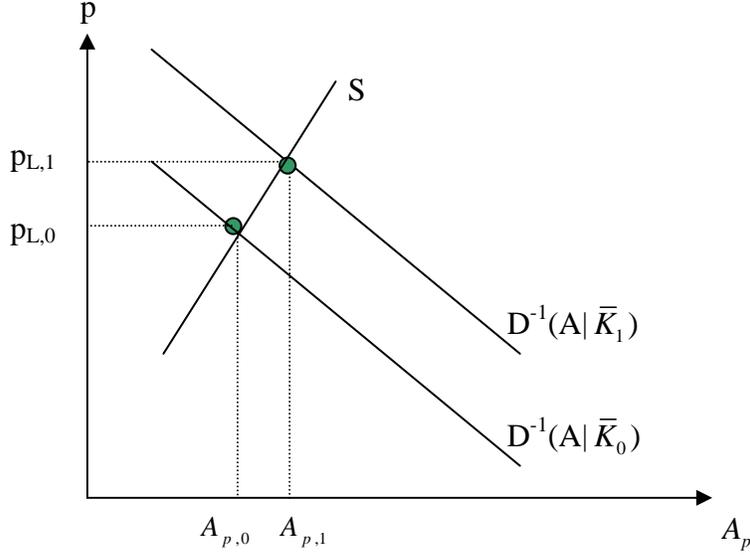


Figure 2: Demand for land for production

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,  $p$ , determine  $\omega$  and  $v$ . They also 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.*

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 work done on factor content of trade, which originated by the classic work of Vanek 1968.<sup>17</sup>

<sup>17</sup>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.

**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  $p_L = p_L^*$ , 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.,  $p_L > p_L^*$ , 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.<sup>18</sup> 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).<sup>19</sup> 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 emissions taxes and 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 (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.<sup>20</sup> 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.

<sup>18</sup>To this end, Proposition 3 follows from Brecher and Choudhri (1982) and Helpman (1984), which show that, on average, 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.

<sup>19</sup>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. 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.

<sup>20</sup>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.

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 industries 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 environment indifference curve  $u_n(n) = \bar{u}_n$  is characterized next.

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

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

Lemma 4 tells us that the environment indifference curves slope downward in the  $A_p - E$  plane. In Fig. 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 indirect 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).

If indirect emissions from reallocating land to production is 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 wild life. A land tax has the opposite effect of a carbon tax on land allocations by reducing biofuel production.<sup>21</sup>

<sup>21</sup>Note that if emissions related to the inputs used in production of biofuel increase green house gases emissions relative to its fossil substitute (e.g., the use of coal to convert corn to ethanol, as oppose to natural gas), the logic is reversed; a carbon tax decreases the ratio  $E^b / E^f$ . Furthermore,

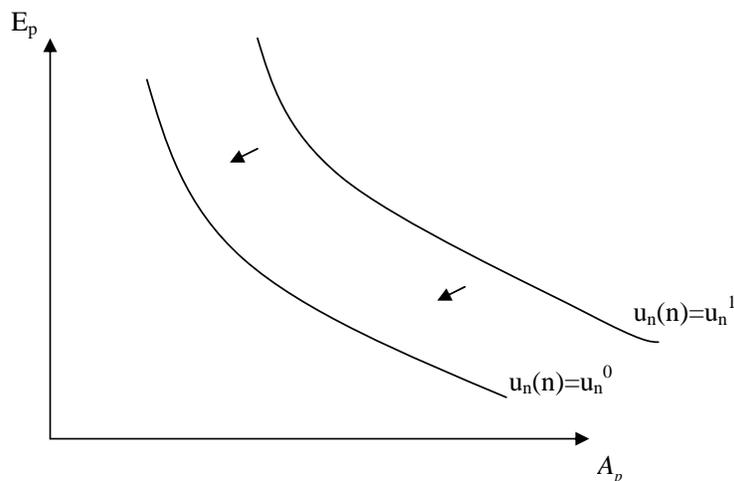


Figure 3: The environment indifferent curve

**Proposition 5** *Assume the indirect land use is 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 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.

Although the determination of the socially optimal solution includes these costs in the calculation, a regulatory regime that prices the externalities sub-optimally might do more harm than good. Specifically, the use of only one policy instrument, e.g., a carbon tax (as suggested by the Kyoto Protocol), may be Pareto inferior to using no instrument. Governments might set taxes sub-optimally 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. In such circumstances, carbon tax and land taxes may be set too low or not imposed at all. For instance, concentrating on fuel taxes, and neglecting litigation that leads to land tax, may lead to sub-optimal regimes; regimes which will affect green house gases, but not necessary reduce them. The use of only one of these instruments, in the context of these two externalities, may be sub-optimal. One might be better off if no policy instruments are used.

**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 indirect 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 Rypczynski 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  $\Phi = -\frac{\partial u_n}{\partial n} \frac{\partial g_n}{\partial Z}$  with respect to  $A_n$ , we see:

$$\frac{d\Phi}{dA_n} = -\frac{\partial^2 u_n}{\partial n^2} \left( \frac{\partial g_n}{\partial A_n} + \frac{\partial g_n}{\partial Z} \frac{\partial Z}{\partial A_n} \right) \frac{\partial g_n}{\partial Z} - \frac{\partial u_n}{\partial n} \left( \frac{\partial^2 g_n}{\partial A_n \partial Z} + \frac{\partial^2 g_n}{\partial Z^2} \frac{\partial Z}{\partial A_n} \right)$$

**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.,  $\frac{\partial^2 g_n}{\partial Z^2} < 0$ , then the emissions tax increases 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 rain forests. 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  $\frac{\partial^2 g_n}{\partial A_n \partial Z} > 0$  and  $\frac{\partial^2 g_n}{\partial Z^2} < 0$ .<sup>22</sup> In other words, if the utility from nature is sufficiently concave, i.e., the curvature of  $u_n(\cdot)$ , i.e.,  $\left| \frac{\partial^2 u_n}{\partial n^2} \right| / \frac{\partial u_n}{\partial n}$ , 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 Rypczynski 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).

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 emission reductions and biodiversity for 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 social optimum level.

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<sup>22</sup>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.,  $g_n(A_n, Z) = \ln\left(\frac{A_n}{Z}\right)$ ). Land mitigates the cost of emission when it absorbs carbon from the atmosphere, i.e., carbon sequestration.

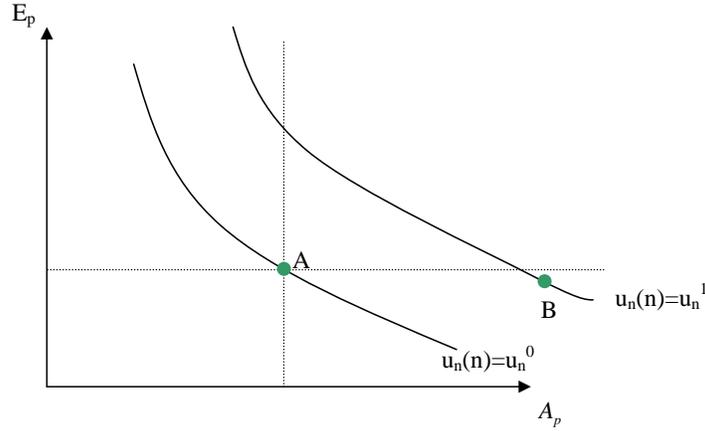


Figure 4: The environment indifferent curves and comparative static

**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 social optimum level, the regulator uses land tax 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 allocates additional land to the environment by making the cost of converting land to production more costly than at the social optimum. Food production contracts and higher food prices result. On the other hand, if indirect emissions are small then lower carbon tax makes fossil fuel cheaper, and when associated with higher land tax makes biofuel more expensive. Resources used to extract fossil fuel are over utilized, whereas biofuel is produced at suboptimal levels.

## 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 upward 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  $\mu \tilde{G}(\cdot)$ , where  $\mu$  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 fix prices. Introducing a big economy does not alter the results. The third section, which focuses on technical changes in biofuels assume a big economy, i.e., commodity prices change, and points to the benefit from improving energy crop yield while reducing demand for land; namely, second generation biofuel crops.

## 5.1 Technical changes in the manufacture 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

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

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  $k$ ,

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

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

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

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

Let us further define

$$\Gamma_{ke,e}^q \equiv \frac{\frac{\partial^2 \widetilde{G}_q(\cdot)}{\partial e_q \partial k_q}}{\frac{\partial \widetilde{G}_q(\cdot)}{\partial e_q}}$$

where  $\text{sign}(\Gamma_{ke,e}^q) = \text{sign}(\frac{\partial^2 \widetilde{G}_q(\cdot)}{\partial e_q \partial k_q})$ . The variable  $\Gamma_{ke,e}^q$  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 suggest the two are substitutes. Similarly define  $s_e^{yx}$ ,  $\Delta_{e,q}$ , and  $\Gamma_{ek,k}^q$ . 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  $s_k^{yx} > \frac{(\eta_{xe}(1-\Delta_{k,x}\cdot\Gamma_{ke,e}^x)-1)\eta_{yk}}{(\eta_{ye}(1-\Delta_{k,y}\cdot\Gamma_{ke,e}^y)-1)\eta_{xk}}$  then  $\frac{\partial \omega}{\partial \mu_y} < 0$ .
2. if  $s_e^{yx} > \frac{(\eta_{xe}(1-\Delta_{k,x}\cdot\Gamma_{ke,e}^x)-1)\eta_{yk}}{(\eta_{ye}(1-\Delta_{k,y}\cdot\Gamma_{ke,e}^y)-1)\eta_{xk}}$  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  $\omega$  to decline with technical changes in the capital good sector  $\mu_y$  is that  $s_k^{yx}$  and  $s_e^{yx}$  are sufficiently large. Assuming energy and capital are complements, i.e.,  $\Gamma_{ke,e}^x > 0$ , Condition 1 essentially requires that the curvature of the food production function with respect to capital and energy is sufficiently large, 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.,  $\omega$  and  $\nu$ , 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 8** *Assume a neutral technical change in the production of manufactured goods and 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; namely, the pattern of production changes at the expense of the landless workers. Furthermore, because the manufacture goods are energy intensive, demand for energy increases, as do emissions. Therefore, given first-generation biofuels, technical changes in the production of manufacturing 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

$$p = \frac{1}{\mu_x} \cdot \frac{\partial \tilde{G}_y(\cdot) / \partial k_y(\cdot)}{\partial \tilde{G}_x(\cdot) / \partial k_x(\cdot)} \text{ and } p = \frac{1}{\mu_x} \cdot \frac{\partial \tilde{G}_y(\cdot) / \partial e_y(\cdot)}{\partial \tilde{G}_x(\cdot) / \partial e_x(\cdot)} \quad (11)$$

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

**Proposition 9** *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 manufacture goods reduce food production and increase food prices if Condition 1 holds. Remember also that Condition 1 holds if food production is sufficiently concave. To mitigate the linkage between the energy sector and the food sector, then, we seek technical changes in food production that make food production less concave; in other words, we seek ag biotech.

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., Zilberman and Qaim, 2003; Huang et al. 2002; Qaim and de Janvry, 2005; Traxler, 2001; Thirtle, 2003). 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 10** *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 10, 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 (the marginal productivity of labor in biofuel denoted  $MP_L^b$  in Fig. 6 shifts up and to the left to  $MP_L^{b'}$ ). Technical change in biofuel also increases the marginal productivity of land in biofuel (we observe a horizontal shift, as depicted in Fig. 5). 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, 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 environmental friendly (e.g., Rajagopal and Zilberman 2008). Whereas ethanol reduces emissions by less than 20 percent (Farrell et al. 2006), some cellulosic crops are believed to reduce emissions by 90 percent.

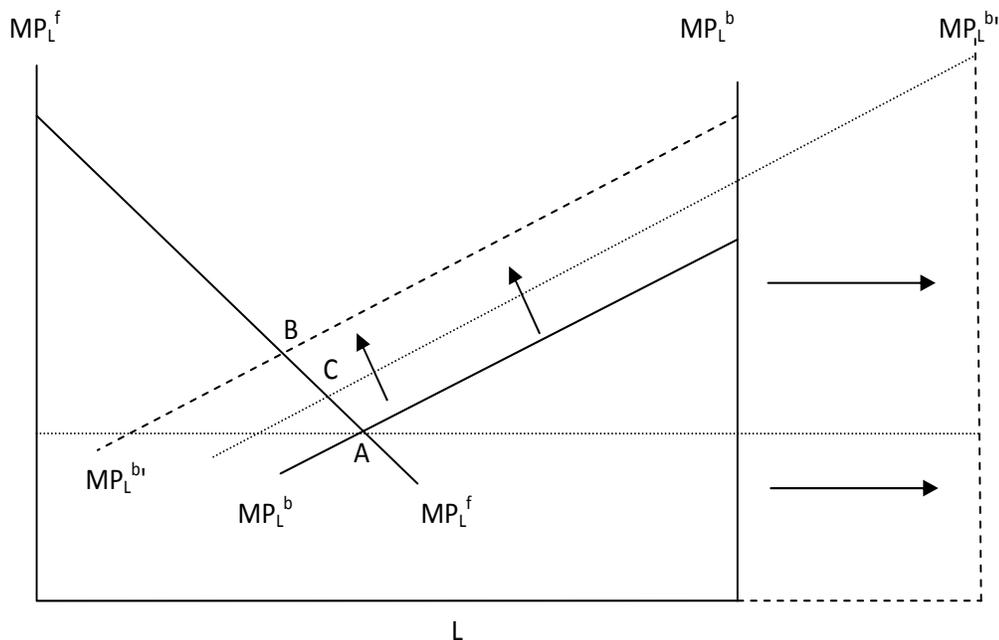


Figure 5: Neutral technical changes in production of bio-fuel

## 6 Discussion and Concluding Remarks

This work creates a mathematical model appropriate for modeling the new energy paradigm characterized by rising energy prices and the emergence of a clean, renewable energy alternative. It yields results that are consistent with empirical observation and that can inform the development of new policies to optimally manage resources.

Globalization increases the production possibilities and introduces an indirect (albeit efficient) method of production that increases production and creates new demand for energy, yielding higher energy prices. Globalization also creates new demand for land for production, thus leading to a loss of the environment. Demand for energy also increases with capital accumulation, which increases the amount of manufactured goods produced and capital services consumed. Capital flows, therefore, also come at the expense of food production and the environment. 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 increase in demand for energy, and led China to become a major importer of oil. China also halted some biofuel production because the loss of agricultural land 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 (Graff and Zilberman 2008). 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 tax or similar policies. We show that emissions taxes may reduce the benefit from the environment if natural land is undervalued. An emissions tax shifts energy production away from fossil fuel to biofuel, which increases the land in bioenergy production and reduces the land in nature. If biodiversity loss is more costly than climate change, as some have suggested it is, then a carbon tax absent a land tax will increase not decrease damage to the environment. Likewise, a land tax absent a carbon tax can be suboptimal to the environment. In fact, we show 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).

## 7 Appendices

### 7.1 Appendix A

#### 7.1.1 Dimensionality

The initial step, in which the dimensionality of our problem is reduced, is solved formally in Appendix B. To this end, let  $s_q = \frac{s}{p_q}$  be the real rent of land in terms of good  $q$ , and define

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

Then, it is shown that the profit maximization problem can be rewritten as

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

The land factor plays an indirect role through its effect on the real rent to land.<sup>23</sup>

Specifically, assume producers minimize the cost of production and are price takers. Their problem can be described as follows:

$$\max_{\{L_q, A_q, K_q, E_q\}} \{p_q \cdot g_q(L_q, A_q, K_q, E_q) - w \cdot L_q - s \cdot A_q - r \cdot K_q - p_E \cdot E_q\} \quad (12)$$

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

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

As defined in Section 7.1.2,  $s_q = \frac{s}{p_q}$  is the real rent of land in terms of good  $q$  and

$$G_q(L_q, K_q, E_q, s_q) \equiv \max_{A_q} \{g_q(L_q, A_q, K_q, E_q) - s_q \cdot A_q\}. \quad (13)$$

The solution to Eq. (13) is  $A_q = H_q(L_q, K_q, E_q, s_q)$ .  $A_q$  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  $g_q(L_q, A_q, K_q, E_q)$  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  $G_q(L_q, K_q, E_q, s_q)$  is also homogeneous of degree one in  $K_q$ ,  $L_q$ , and  $E_q$ , given  $s_q$ .

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

Thus, the profit maximization problem, as depicted in Eq. (12), can be rewritten as

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

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

### 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,

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

<sup>23</sup>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).

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 ( $\infty$ ) as the capital-labor ratios  $k_q$  tends to 0 ( $\infty$ ). Similarly,  $\frac{MP_q^L}{MP_q^E}$  goes to 0 ( $\infty$ ) as the energy-labor ratios  $e_q$  tends to 0 ( $\infty$ ). 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

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

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

Next, we show that the price of food,  $p$ , together with the land tax  $\Psi$ , and the carbon tax  $\Phi$ , determine  $s$ ,  $\omega$ , and  $\nu$  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

$$\begin{aligned}p &= r \cdot a_{K_x} + w \cdot a_{L_x} + s \cdot a_{A_x} + p_E \cdot a_{E_x}, \text{ and} \\ 1 &= r \cdot a_{K_y} + w \cdot a_{L_y} + s \cdot a_{A_y} + p_E \cdot a_{E_y}.\end{aligned}\tag{14}$$

Assume production of both fossil fuel and biofuel in equilibrium.<sup>24</sup> If production of fossil fuel is not at full capacity, i.e.  $g_E^f(L_E^f, K_E^f) < \bar{E}^f$ , then

$$r \cdot a_{K_E^f} + w \cdot a_{L_E^f} + \Phi \frac{\partial g_z}{\partial E^f} = p_E = s \cdot a_{A_E^b} + w \cdot a_{L_E^b}.\tag{15}$$

If, on the other hand, the constraint is met, then  $E^f = \bar{E}^f$  and Eq. (14) becomes

$$\begin{aligned}p_E - \Phi \frac{\partial g_z}{\partial E^f} &\geq r \cdot a_{K_E^f} + w \cdot a_{L_E^f}, \text{ and} \\ p_E &= s \cdot a_{T_E^b} + w \cdot a_{L_E^b}.\end{aligned}\tag{16}$$

Because the land tax is strictly positive and  $\bar{A} - A_N > 0$ ,  $s = \Psi$  in equilibrium. Pressure to change  $s$  is mitigated by a change in the amount of land allocated to production,  $\bar{A} - A_N$ .

<sup>24</sup>Note that, contrary to the assumptions made about sectors  $x$  and  $y$ , biofuel production may be zero. Hence, in equilibrium  $p_E - \Phi = r \cdot a_{K_E^f} + w \cdot a_{L_E^f}$  whereas  $p_E < s \cdot a_{A_E^b} + w \cdot a_{L_E^b}$ .

## 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

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

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

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

which is the Rypczynski effect.

### Proof of Proposition 2

First, we express goods consumed and produced in terms of their factor content.<sup>25</sup> 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  $\omega$  and  $\mu_y$ , while using the implicit function theorem, and rearrange terms

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

The ratio of the marginal return to labor and the marginal return to capital equals  $\omega$ , i.e.,

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

<sup>25</sup>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), Treffer (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  $\frac{\partial k_y}{\partial \omega}$ :

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

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

Then,

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

$$\frac{\frac{\partial^2 \tilde{G}_x(\cdot)}{\partial k_x^2} \frac{\partial k_x}{\partial \omega}}{\frac{\partial \tilde{G}_x(\cdot)}{\partial k_x}} < \frac{\frac{\partial^2 \tilde{G}_y(\cdot)}{\partial k_y^2} \frac{\partial k_y}{\partial \omega}}{\frac{\partial \tilde{G}_y(\cdot)}{\partial k_y}} < 0$$

Hence, as

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

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

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

where

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

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

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

$$= \frac{\frac{1}{\eta_{xk} k_x}}{(\eta_{xe} (1 - \Delta_{k,x} \cdot \Gamma_{ke,e}^x) - 1)}$$

and

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

we get

$$\frac{\partial \omega}{\partial \mu_y} < 0 \Leftrightarrow \frac{\eta_{xk} \frac{1}{k_x}}{(\eta_{xe} (1 - \Delta_{k,x} \cdot \Gamma_{ke,e}^x) - 1)} < \frac{\eta_{yk} \frac{1}{k_y}}{(\eta_{ye} (1 - \Delta_{k,y} \cdot \Gamma_{ke,e}^y) - 1)} < 0$$

$$\Leftrightarrow s_k^{yx} > \frac{(\eta_{xe} (1 - \Delta_{k,x} \cdot \Gamma_{ke,e}^x) - 1) \eta_{yk}}{(\eta_{ye} (1 - \Delta_{k,y} \cdot \Gamma_{ke,e}^y) - 1) \eta_{xk}}$$

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

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

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

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

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  $\omega$  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.

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