Is bioenergy trade good for the environment?

Jean-Marc Bourgeon[*] Hélène Ollivier[†]

DRAFT: PLEASE DO NOT QUOTE
June 15, 2009

Abstract

This paper analyzes the impacts of bioenergy trade on greenhouse gases emissions using a two-good, three-factor model. Bioenergy is an intermediate good produced by the agricultural sector and used by the industry as a substitute for fossil fuels. Countries impose Pigovian taxes on pollution emitted by both sectors without international coordination. We assume that agriculture is less pollution intensive than industry (after taxation) and that Northern countries have a comparative advantage over Southern ones in the industrial sector. Under autarky, pollution levels are identical whatever the region. With trade liberalization, Northern emissions increase and Southern ones decrease, except for the agricultural sector, resulting in a reduced worldwide level of emissions. The welfare impacts are uneven since North benefits from trade liberalization whereas South experiences a revenue deterioration.

Keywords: bioenergy; intermediate product ; North-South trade ; global pollution

JEL Classification: F18; H23; Q17

1 Introduction

The potential of bioenergy in mitigating greenhouse gases (GHG) emissions from fossil fuels has recently stimulated both the scientific and the political debate (von Lampe, 2006). On the one hand, fostering bioenergy, as well

[*]INRA and Ecole Polytechnique

[†]Corresponding author: EHESS - umr CIRED, 45 bis avenue de la Belle Gabrielle, 94736 Nogent s/ Marne, France. Tel. +33 143947365. ollivier@centre-cired.fr. I acknowledge receiving some funding from AgFoodTrade, a project supported by the EU Commission, Grant 212036, 2008.

as other renewable energy sources, is justified by the environmental benefits arising from avoided polluting emissions; on the other hand, expanding bioenergy production may result in an increase in the burden on local ecosystems, e.g., by encouraging deforestation. Moreover, because bioenergy also competes with agriculture on arable land, food prices increase.

So far, international trade of bioenergy has been limited.[1] Bioenergy trade is beset by both domestic and border distortions securing national energy supply or protecting domestic farmers. However, ambitious mandates set by governments, such as the US Energy Policy Act of 2005 or the EU target of 5.75 percent proportion of biofuels for transportation by 2010, will certainly induce an active and sizeable international trade in biofuels.

The objective of this paper is to appraise the potential impacts of a liberalization of bioenergy trade on the global economy, with a particular focus on the resulting level of GHG emissions. A distinctive feature of bioenergy is that it generates sectoral interactions, since bioenergy is both an output of the agricultural sector and an input for the industrial sector. In the trade and environment literature, the sectoral interaction between a "clean" activity (agriculture) and a Smokestack sector (industry) is based upon a cross-sectoral externality, when industrial pollution reduces agriculture productivity or biodiversity, which makes spatial separation of activities a new motive for international trade (Copeland and Taylor 1999, Polasky et al. 2004). We depart from these external effects by assuming that GHG emissions only harms consumers through climate change. Moreover, no sector can be considered as "carbon free": Although bioenergy use does not emit additional anthropogenic gases, production of bioenergy generates GHG emissions through the use of fertilizers or chemicals for an intensive type of agriculture or through the conversion of forested lands for an extensive type of agriculture.[2]

We adopt a theoretical approach in line with Copeland and Taylor (1994, 1995, 2003) to determine the trade equilibrium of a global economy with many countries belonging to two regions, North and South, and facing a global pollution with no international coordination. Governments set their

[1] Of 2.8 billion litres of ethanol exports in 2008, Brazil exported 97 percent, primarily to Europe, Japan, India and the US. Net exports of biodiesel were 1.1 billion litres in 2007, the largest exporters being the US, Indonesia and Argentina, mainly to EU and Japan. (Source: 'World Biofuel Maritime Shipping Study', by IEA Bioenergy Task 40, April 2009. www.bioenergytrade.org)

[2] Highlighted by Fargione et al. (2008), converting land to some specific biofuel crops can generate 17 to 123 times more carbon than the annual savings of fossil fuel replacement (for instance, in the case of palm oil plantations in Indonesia and Malaysia).

environmental regulations independently, taking the other countries' emissions as given. The main source of differentiation across regions is a higher endowment in effective labor in Northern countries, the labor force being more productive in North than in South. As the production of bioenergy requires the use of natural capital, the trade of bioenergy could lead to an over-exploitation of the resource (deforestation) due to the weakness of property rights in Southern countries, as often highlighted by the literature (Chichilnisky, 1994). Here, there is no institutional failure since we assume both regions are able to implement Pigovian tax on pollution coming from industrial emissions and from agricultural use of natural capital. However, Southern countries are more prone to use more natural capital with trade liberalization than Northern ones since the latter have a comparative advantage in the industrial sector.

Under autarky, emission levels of both sectors are identical in the Northern and Southern countries. With trade liberalization, many industries relocate in North and the agricultural sector expands in South. Since industries are the most pollution-intensive sector, Northern countries will be responsible for more GHG emissions than Southern ones. At the global scale, pollution levels are reduced by trade. This result can be compared to the no factor price equalization equilibrium in Copeland and Taylor (1995) where, using a model with a continuum of industries, they show that his low income gives a strategic advantage to South to increase its pollution levels, leading to an increase in global pollution in trade. The decrease in global pollution in our model is mainly due to a technique effect since Northern industries are cleaner than Southern ones (the higher Northern environmental tax forces domestic industrial producers to use more bioenergy intensive techniques). Consequently, the impact on representative consumers' welfare is different across regions: While Northern and Southern consumers benefit from the global reduction in emissions, Northern countries enjoy an increase in their revenue whereas Southern countries' revenue decreases. This adverse impact of trade on Southern revenue makes a strong case against any involvement of Southern countries in international agreements that would result in more demanding environmental policy than the one freely decided in the absence of coordination.

The remaining of the paper is organized as follows: Section 2 presents the model and Section 3 examines the autarky equilibrium. Section 4 considers the effects of trade on the environment and welfare of North and South. The last section contains some concluding remarks.

2 The model

We consider a world economy consisting of two regions (North and South), each composed of many countries : n in North and n^* in South.[3] All countries within a region are identical. Since the population size do not play any role in our analysis, we normalize the population of each country to 1. The key difference between Northern and Southern countries resides in the labor force, assumed more productive in North. Therefore, there is a difference in labor endowments between Northern and Southern countries. Denoting by L and L^* the level of effective labor in the Northern and Southern countries respectively, we have: $L > L^*$.

The economy of each country is composed of two sectors: agriculture (A) and industry (M). These two sectors are responsible for greenhouse gases emissions, a pollution leading to global warming and affecting the welfare of the world population. The industrial sector pollutes through the use of fossil fuel during the production process. Agriculture indirectly pollutes through the use of natural capital available in each country: Agricultural producers either increase their soil productivity by using fertilizers, whose production and use release local and global pollutions (considered in equivalent carbon emissions), or expand the amount of productive lands by deforesting.[4]

More precisely, the production of A units of agricultural goods is described by

$$A = K_A^{\mu} L_A^{1-\mu},$$

where K_A corresponds to the amount of natural capital and L_A the quantity of labor allocated to agriculture. The use of capital K_A generates $Z_A = \psi(K_A)$ units of the transboundary externality with $\psi' > 0$ and $\psi'' > 0$ (In the following, we assume $\psi(K_A) = \lambda K_A^{\sigma}/\sigma$, with $\lambda > 0$). The agricultural product can be used either as a final food product (F) for consumers or as an intermediate product, bioenergy (B), which enters the production process of the manufacturing sector. We then have

$$A = F + B.$$

The Smokestack sector M requires both labor, L_M, and energy as inputs,

[3] In the following, we index by $''*''$ the variables corresponding to Southern countries. Most of the computations are made for a Northern country but are valid for a Southern one except explicit mention.

[4] Northern intensive agricultural producers are more likely to use chemical inputs, whereas Southern extensive producers are more likely to deforest. Hence, agriculture being a source of carbon emissions covers two specific issues depending on the location of the production.

the latter being a mix of fossil energy, E, and bioenergy, B. The industrial process emits pollution Z_M which is proportional to the use of fossil fuel (we normalize the carbon content of fossil energy to 1 so that $Z_M = E$). Equivalently, we may consider that there are three inputs, labor, pollution and bioenergy, that are imperfect substitutes, and are combined in a constant returns production process. The production function of the industry can thus be indifferently written as

$$M = L_M^{1-\alpha}\left[E^{1-e}B^e\right]^\alpha = L_M^{1-\alpha}Z_M^{(1-e)\alpha}B^{e\alpha},$$

where $0 < \alpha < 1$ indexes the total of energy uses and $0 < e < 1$ the share of bioenergy in the energy mix.

Pollution only harms consumers and there is no cross-sectoral externality. To reduce human-induced carbon emissions, governments adopt sectoral policies, using specific taxes for industry and for agriculture. Considering the tax on industrial pollution τ, the producers' trade-off is between paying the environmental tax and abating pollution. Abatement occurs through technological change that incorporates more bioenergy. In fact, bioenergy use is considered as carbon-free since the carbon emitted through the combustion of bioenergy was previously taken from the atmosphere through the photosynthesis process. To abstract from consideration on stock depletion we assume that energy as well as natural capital are available in both regions without restriction. Therefore, the fossil fuel price and the natural capital price (or land price) correspond to their respective tax: τ and τ_A.[5]

Denote by w the effective labor wage and by p_A the price of the agricultural good, which is also the numeraire. Labor being perfectly mobile within a country (but immobile across countries), the wage is identical across sectors. The unit-cost of the representative firm in the industrial sector is given by

$$c_M(w,\tau) = \kappa_M p_A^{e\alpha} w^{1-\alpha}\tau^{(1-e)\alpha} \tag{1}$$

where $\kappa_M \equiv \alpha^{-\alpha}(1-\alpha)^{\alpha-1}e^{-e\alpha}(1-e)^{-(1-e)\alpha}$ is a constant. Given constant returns to scale, industrial producers make no profit at equilibrium. Denoting by p the price of the industrial good, the production cost divides among the

[5]We assume that the government detains all the informations necessary to tax the carbon content of fossil energy used by the industrial sector and the natural capital used by the agricultural sector without cost.

inputs following the Euler's rule, i.e. we have :

$$\tau Z_M = (1-e)\alpha p M, \tag{2}$$

$$w L_M = (1-\alpha) p M, \tag{3}$$

$$p_A B = e\alpha p M. \tag{4}$$

Symmetrically, for agriculture, the total cost of producing A is $Ac_A(w, \tau_A)$, where

$$c_A(w, \tau_A) = \kappa_A w^{1-\mu} \tau_A^{\mu}$$

and where $\kappa_A \equiv \mu^{-\mu}(1-\mu)^{\mu-1}$; it leads to:

$$w L_A = (1-\mu) A \tag{5}$$

$$\tau_A K_A = \mu A. \tag{6}$$

As pollution is transboundary, consumers' utility is affected by world pollution Z^w, the sum of the emissions of the Northern and Southern regions: $Z^w = Z^N + Z^S$. Considering all countries as identical within the same region, we have $Z^N = nZ$ with $Z = Z_M + Z_A$ for North. The utility of the representative consumer is given by:

$$U = b_A ln D_A + b_M ln D_M - \beta (Z^w)^{\gamma}/\gamma, \tag{7}$$

where D_A and D_M are the quantities of good A and M consumed by the representative consumer, with b_A and $b_M = 1 - b_A$ the corresponding shares of income. We assume that $\beta > 0$ and $\gamma \geq 1$ to ensure that the marginal willingness to pay for abating pollution is a nondecreasing function of the world pollution level. The expenditure function corresponding to the representative consumer's program is given by:

$$\begin{aligned} E(\bar{u}, Z^w) &\equiv \min_{D_A, D_M} \{p_A D_A + p D_M : U \geq \bar{u}\} \\ &= E_0 \exp(\bar{u} + \beta (Z^w)^{\gamma}/\gamma) \end{aligned} \tag{8}$$

where

$$E_0 = \exp\left\{b_A \ln b_A + b_M \ln b_M - b_M \ln p - b_A \ln p_A\right\}.$$

The consumer's demands in terms of industrial good and food satisfy

$$D_M = b_M E(\bar{u}, Z^w)/p, \tag{9}$$

$$D_A = b_A E(\bar{u}, Z^w)/p_A. \tag{10}$$

The balanced budget constraint implies that national expenses $E(\bar{u}, Z^w)$ should not exceed national revenue I. Assuming the proceeds of the environmental taxes are redistributed to consumers through a lump-sum transfer, we have

$$I \equiv wL + \tau Z_M + \tau_A K_A, \tag{11}$$

since full employment must be achieved, i.e. $L = L_A + L_M$. With national environmental policies, optimality is not achieved because of the transboundary nature of the externality. A Nash equilibrium between countries results from the absence of global negotiation. Each government defines the pollution targets Z_M and Z_A (or equivalently, the level of natural capital used by the agricultural sector K_A) for its country, considering the emissions from all other countries as exogenous. It imposes both a tax on industrial emissions and a user price for natural capital so that the utility of the representative consumer is maximized. Differentiating the budget balance constraint $E(\bar{u}, Z^w) = I$ allows to determine the effects of small variations of industrial emissions dZ_M and natural capital dK_A around their optimal levels. We have, neglecting price effects[6]

$$E(\bar{u}, Z^w)[d\bar{u} + \beta (Z^w)^{\gamma-1}(dZ_M + \psi'(K_A)dK_A)] = \tau dZ_M + \tau_A dK_A$$

At the optimum, $d\bar{u} = 0$, leading to the conditions

$$\tau = \beta I \, (Z^w)^{\gamma-1} \tag{12}$$

$$\tau_A = \psi'(K_A)\tau. \tag{13}$$

Hence, the emission tax τ increases with the national income and the global pollution level. This is also the case for the price of natural capital τ_A which also increases with the amount of natural capital used by agricultural producers.

The optimal taxes derived from (12) and (13) correspond to the prices attached by the government to GHG emissions and thus implicitly define the emission supply of the country. More specifically, using (11) and $\psi'(K_A)K_A = \sigma Z_A$, we obtain the following relationship

$$\frac{\tau}{w} = \frac{\beta L \, (Z^w)^{\gamma-1}}{1 - \beta [Z_M + \sigma Z_A] \, (Z^w)^{\gamma-1}}. \tag{14}$$

which also depends on the national labor endowment L. The demand side of GHG comes from the industrial and the agricultural sectors. These demands

[6] We thus abstract from the use of environmental policies as commercial levies.

are easily derived from (2)-(6). Hence, given (13), we have

$$\frac{Z_A}{L_A} = \frac{1}{\sigma}\frac{\mu}{1-\mu}\frac{w}{\tau} \tag{15}$$

for agriculture, and

$$\frac{Z_M}{L_M} = \frac{\alpha(1-e)}{1-\alpha}\frac{w}{\tau} \tag{16}$$

for industry. (15) and (16) allow us to compare factor intensities across sectors. Surprisingly, GHG emissions per unit of effective labor in agriculture are smaller the higher the elasticity of emissions due to the use of natural capital σ. This is the result of the optimal tax on natural capital which, given (13), verifies $\tau_A K_A = \sigma\tau Z_A$. Therefore, the tax $\tau_A K_A$ on natural capital is higher than its equivalent in terms of carbon emissions τZ_A since $\sigma > 1$. To internalize entirely the externality of GHG emissions from the use of natural capital, agricultural producers have to pay a tax proportional to the marginal damage $\psi'(K_A) = \lambda K_A^{\sigma-1}$, which increases with K_A since $\sigma > 1$. Comparing (15) and (16), the industrial sector is relatively pollution intensive and agriculture labor intensive if

$$\mu < \frac{\sigma(1-e)\alpha}{1-\alpha[1-\sigma(1-e)]} \tag{H1}$$

which is assumed in the rest of the paper. For $e = 0$ (no substitution between fossil energy and bioenergy), H1 becomes $\mu < \sigma\alpha/[1-\alpha(1-\sigma)]$ and is satisfied for all $\sigma \geq 1$ if $\mu < \alpha$. Hence, when it is impossible to substitute bioenergy to fossil fuels, agriculture is cleaner than industry if the output elasticity of natural capital in agriculture is lower than the output elasticity of energy in industry. However, when e is large, close to 1, i.e. for highly bioenergy intensive industrial sector, μ must be very low for agriculture to be cleaner than industry. It is convenient to rewrite H1 as

$$\sigma > \frac{\mu(\xi-1)}{1-\mu} \tag{17}$$

where $\xi \equiv (1-e\alpha)/[(1-e)\alpha] > 1$.

The relative shares of labor in each sector are deduced from (14), (15) and (16). We obtain

$$\frac{L_A}{L} = \frac{1-\mu}{\mu}\frac{\sigma Z_A \beta (Z^w)^{\gamma-1}}{1-[Z_M+\sigma Z_A]\beta(Z^w)^{\gamma-1}} \tag{18}$$

for agriculture and

$$\frac{L_M}{L} = \frac{1-\alpha}{\alpha(1-e)} \frac{Z_M \beta (Z^w)^{\gamma-1}}{1 - [Z_M + \sigma Z_A] \beta (Z^w)^{\gamma-1}}$$

for industry. The labor market equilibrium, $L_A + L_M = L$, leads to the following relationship between sectoral emissions

$$\frac{\sigma}{\mu} Z_A + \xi Z_M = \frac{1}{\beta (Z^w)^{\gamma-1}}. \tag{19}$$

which holds whatever the country's openness to trade. At equilibrium, demand and supply are equal. Pollution demand is related to the consumers' consumption of goods which depends on the openness of the countries to trade. As a benchmark, we first investigate the case of autarky. We then detail the effects of an opening of the countries to trade.

3 Autarky

Under autarky, both regions consume only locally produced agricultural and industrial goods. The equilibrium in the industrial good market gives $pM = pD_M = b_M I$, while we have $A = D_A + B = [b_A + e\alpha b_M] I$ for agricultural goods. Using $\tau Z_M = (1-e)\alpha b_M I$, $\tau_A K_A = \mu(e\alpha b_M + b_A) I$, (12) and (13), allows us to deduce the pollution demand from each sector:

$$Z_M = \frac{(1-e)\alpha b_M}{\beta (Z^w)^{\gamma-1}} \tag{20}$$

$$Z_A = \frac{\mu(e\alpha b_M + b_A)}{\sigma \beta (Z^w)^{\gamma-1}}. \tag{21}$$

Consequently, the total demand of pollution is given by

$$Z = Z_M + Z_A = \frac{\theta}{\beta (Z^w)^{\gamma-1}}$$

where $\theta \equiv (1-e)\alpha b_M + \mu(e\alpha b_M + b_A)/\sigma$. Pollution demands (20) and (21) depend only on the world pollution level and on parameters that are the same in both regions. Hence, the countries total emission levels are the same across regions under autarky: $Z = Z^* = Z^a$ and the resulting word level of GHG emissions under autarky is given by

$$Z^{wa} = nZ + n^* Z^* = \left[\frac{(n+n^*)\theta}{\beta} \right]^{\frac{1}{\gamma}}. \tag{22}$$

Hence, under autarky, despite different labor endowment ($L > L^*$), Northern and Southern countries adopt the same patterns of emissions in the industry:

$$Z_M = Z_M^* = Z_M^a \equiv \frac{(1-e)\alpha b_M}{\beta} \left[\frac{(n+n^*)\theta}{\beta} \right]^{\frac{1-\gamma}{\gamma}},$$

and in agriculture:

$$Z_A = Z_A^* = Z_A^a \equiv \frac{\mu(b_A + e\alpha b_M)}{\sigma\beta} \left[\frac{(n+n^*)\theta}{\beta} \right]^{\frac{1-\gamma}{\gamma}}.$$

Consequently, we have the following result:

Proposition 1 *Under autarky, Northern and Southern countries emit the same level of pollution, $Z = Z^* = Z^a$, and use the same amount of natural capital, $K_A = K_A^* = K_A^a$.*

Under autarky, pollution is not a distinctive pattern for North and South. Even though productions levels are different in North compared to South, emissions of GHG are identical from one country to another. Factor prices in North and South are different though, the difference being similar to the labor endowment discrepancy. Indeed, using (2), (3), (12) and (14), we obtain that

Proposition 2 *Under autarky, relative factor prices are higher in North*

$$\frac{\tau/w}{\tau^*/w^*} = \frac{L}{L^*} > 1, \tag{23}$$

the environmental taxes and the national income are higher in North

$$\frac{\tau_A}{\tau_A^*} = \frac{\tau}{\tau^*} = \frac{I}{I^*} = \left[\frac{L}{L^*} \right]^{1-\mu} > 1 \tag{24}$$

whereas the effective labor wage is lower in North

$$\frac{w}{w^*} = \left[\frac{L^*}{L} \right]^{\mu} < 1. \tag{25}$$

Allowing for only one difference in terms of effective labor endowment and using identical preferences and technologies leads to a discrepancy between North and South in terms of environmental policy and revenue, at the autarky equilibrium. North represents the richer region and South the developing countries.

The potential gains from trade depend on each region's comparative advantage. Northern countries have a larger effective labor endowment than Southern ones and pollution levels are the same under autarky. Given H1, relative factor abundance theory predict that in trade, North specializes in labor-intensive agriculture whereas South specializes in pollution-intensive industry. However, the intermediate product, bioenergy, and the interlink between sectors challenge these theoretical predictions. Using (24) and (25), we have[7]

$$\frac{c_M(w,\tau)}{c_M(w^*,\tau^*)} = \frac{w^{1-e\alpha}(\tau/w)^{(1-e)\alpha}}{(w^*)^{1-e\alpha}(\tau^*/w^*)^{(1-e)\alpha}} = \left[\frac{L^*}{L}\right]^{\mu(1-e\alpha)-(1-e)\alpha},$$

as a consequence, $c_M(w,\tau) < c_M(w^*,\tau^*)$ if

$$\mu > \frac{\alpha(1-e)}{1-e\alpha} \iff \mu\xi > 1. \qquad \text{H2}$$

Hence it is possible that Northern countries have a comparative advantage in the dirtiest sector, namely industry, while Southern ones have a comparative advantage in the cleanest one, agriculture, if H2 and H1 are compatible. We verify easily their compatibility since $\sigma > 1$. Consequently, we obtain

Lemma 1 *In a world economy with two sectors and three factors, Southern countries have a comparative advantage in the labor intensive agricultural sector and Northern countries in the GHG intensive industry if μ and σ satisfy*

$$\frac{\sigma(1-e)\alpha}{1-\alpha[1-\sigma(1-e)]} > \mu > \frac{\alpha(1-e)}{1-e\alpha}.$$

Figure 1 illustrates the autarky case when H2 is satisfied. As both regions use the same amount of natural capital, agricultural iso-cost curves are identical. However, the iso-cost curve of the Northern industrial sector is located below the Southern one (and thus, the price of the industrial good is larger in South than in North). H2 leads to a steeper agricultural iso-cost

[7]As we have normalized the agricultural price to one in both regions, agricultural production costs are identical and only industrial costs differ across regions. Hence, comparative advantages are reflected by the discrepancy in the unit cost of industrial products.

curve relatively to the industrial curve, which implies a higher pollution price and a lower wage in Northern countries relatively to Southern ones.[8]

The output elasticity of natural capital in agriculture, μ, which determines the share of natural capital required in the agricultural production, should be sufficiently high for North to have a comparative advantage in industry and South in agriculture. We assume for the rest of the paper that both H1 and H2 are satisfied in order to analyze the impacts of trade.

4 Trade liberalization

To analyse the effect of trade on the pollution patterns, we use the iceberg cost approach (Samuelson, 1954) of trade frictions between North to South. More precisely, we assume that trade frictions take the form of a “shrinkage" of the industrial goods in transit so that only a fraction of the items shipped abroad actually arrives. To simplify computations, we assume that there is no frictions in the transport of agricultural goods (both food and bioenergy).[9] Hence, when all countries are open to trade, agricultural good prices p_A are equalized, whereas industrial good prices differ. Denoting by ω the trade friction coefficient, we have $p_M^* = (1+\omega)p_M$. A decrease in trade costs of the iceberg type is usually interpreted as trade liberalization.

Both regions produce the agricultural good but it may be the case that some countries (Southern ones) specialize in agriculture.[10] Considering the case of a diversified production equilibrium, trade implies the following two conditions:

$$c_M(w^*, \tau^*) = (1+\omega)c_M(w, \tau)$$
$$c_A(w^*, \tau_A^*) = c_A(w, \tau_A).$$

Consequently, using (13), we obtain the relative factor prices

$$\tau/\tau^* = [K_A/K_A^*]^{-\nu(\xi-1)}\,\vartheta^{1-\mu} \tag{26}$$
$$w/w^* = [K_A/K_A^*]^{\nu}\,\vartheta^{-\mu}, \tag{27}$$

[8] The equation of the industrial iso-cost curve is given by $\tau = (p/\kappa_M)^{1/[(1-e)\alpha]}w^{-(1-\alpha)/[(1-e)\alpha]}$ and we have $(d\tau/dw)|_{C_M=p} = -(\tau/w)(1-\alpha)/[(1-e)\alpha]$. For agriculture, we obtain $(d\tau/dw)|_{C_A=1} = -(\tau/w)(1-\mu)/\mu$. Consequently, $||(d\tau/dw)|_{C_M=p}|| > ||(d\tau/dw)|_{C_A=1}|| \Leftrightarrow \mu\xi > 1$.

[9] It also allows us to have the same numeraire in every countries: $p_A = p_A^* = 1$. While we could also consider trade frictions for the agricultural good, it is not necessary since we only have two goods.

[10] All countries produce some agricultural goods under the assumption that $\psi'(0) = 0$ which implies that the price of natural capital is negligible when only low levels are involved in the agricultural production.

where $\nu \equiv \mu(\sigma-1)/[\mu\xi-1] > 0$ and $\vartheta \equiv (1+\omega)^{1/[\alpha(1-e)(\mu\xi-1)]}$. Free trade corresponds to $\vartheta = 1$ while there is no trade if $\vartheta \geq \bar{\vartheta} \equiv L/L^*$. Hence, relevant values for ϑ belong to $[1, \bar{\vartheta}]$.

To characterize the trade equilibrium, we have to derive the relative shares of each region in tax revenues, wages and global income. We have

$$\begin{aligned} \tau Z_M^N + \tau^* Z_M^S &= (1-e)\alpha b_M (I^N + I^S) \\ \tau_A K_A^N + \tau_A^* K_A^S &= \mu(e\alpha b_M + b_A)(I^N + I^S), \end{aligned}$$

hence,

$$\tau Z_M^N + \tau_A K_A^N + \tau^* Z_M^S + \tau^* K_A^S = \phi(I^N + I^S)$$

and

$$wL^N + w^* L^S = (1-\phi)(I^N + I^S)$$

where $\phi \equiv (1-e)\alpha b_M + \mu(e\alpha b_M + b_A)$ represents the share of environmental taxes in global income. Denote by δ_Z the northern share of environmental taxes in the global revenue from pollution taxation, i.e.

$$\delta_Z \equiv \frac{\tau Z_M^N + \tau_A K_A^N}{\tau Z_M^N + \tau_A K_A^N + \tau^* Z_M^S + \tau^* K_A^S},$$

by δ_I the Northern share in global income, i.e.

$$\delta_I \equiv \frac{I^N}{I^N + I^S} \tag{28}$$

and by δ_L the Northern share in global labor revenue, i.e.

$$\delta_L \equiv \frac{wL^N}{wL^N + w^* L^S}. \tag{29}$$

We have

$$\tau Z_M^N + \tau_A K_A^N = \phi \frac{\delta_Z}{\delta_I} I^N = \frac{\phi}{1-\phi} \frac{\delta_Z}{\delta_L} wL^N. \tag{30}$$

As we also have

$$\frac{I^N}{\delta_I} = \frac{wL^N}{\delta_L} + \frac{\tau Z^N + \tau_A K_A^N}{\delta_Z},$$

we obtain, using (11) and (30),

$$\delta_I = (1-\phi)\delta_L + \phi\delta_Z.$$

Northern share of global income is a weighted sum of Northern shares of revenues from labor income and from environmental taxes.

Use of (13) and (30) gives the inverse pollution demand function for a Northern country in trade:

$$\frac{\tau}{w} = \frac{\phi}{1-\phi}\frac{\delta_Z}{\delta_L}\frac{L}{Z_M + \sigma Z_A}. \tag{31}$$

Equalizing supply (14) and demand (31) of pollution leads to

$$Z_M + \sigma Z_A = \frac{\phi \delta_Z/\delta_I}{\beta (Z^w)^{\gamma-1}} \tag{32}$$

which, combined with (19), leads to emissions levels for a Northern country

$$Z_M^t = \frac{\mu - \phi\delta_Z/\delta_I}{(\mu\xi - 1)\beta(Z^w)^{\gamma-1}} \tag{33}$$

$$Z_A^t = \frac{\mu(\xi\phi\delta_Z/\delta_I - 1)}{\sigma(\mu\xi - 1)\beta(Z^w)^{\gamma-1}} \tag{34}$$

and gives the following national pollution level

$$Z^t = Z_M^t + Z_A^t = \frac{(\mu\xi - \sigma)\phi(\delta_Z/\delta_I) + \mu(\sigma - 1)}{(\mu\xi - 1)\sigma\beta(Z^w)^{\gamma-1}}. \tag{35}$$

Symmetrically, for a Southern country,

$$\begin{aligned} Z_M^{*t} &= \frac{\mu - \phi(1-\delta_Z)/(1-\delta_I)}{(\mu\xi - 1)\beta(Z^w)^{\gamma-1}} \\ Z_A^{*t} &= \frac{\mu[\xi\phi(1-\delta_Z)/(1-\delta_I) - 1]}{\sigma(\mu\xi - 1)\beta(Z^w)^{\gamma-1}}, \end{aligned} \tag{36}$$

which gives

$$Z^{*t} = \frac{(\mu\xi - \sigma)\phi(1-\delta_Z)/(1-\delta_I) + \mu(\sigma - 1)}{(\mu\xi - 1)\sigma\beta(Z^w)^{\gamma-1}}. \tag{37}$$

Finally, the global level of GHG emissions in trade is given by

$$Z^{wt} = \left[\frac{(n+n^*)\mu(\sigma-1) + \phi(\mu\xi - \sigma)[n\delta_Z/\delta_I + n^*(1-\delta_Z)/(1-\delta_I)]}{\sigma\beta(\mu\xi - 1)}\right]^{1/\gamma}. \tag{38}$$

To characterize the impacts of trade liberalization, we have to determine the relative shares of income. Use of (28), (29), (34) and (36) leads to an implicit equation for the natural capital ratio K_A/K_A^*. More precisely, we have

Lemma 2 *In a diversified trade equilibrium, the Northern shares of income are given by*

$$\delta_I = [1 + (n^*/n)\,[K_A/K_A^*]^{\nu(\xi-1)}\,\vartheta^{-(1-\mu)}]^{-1}$$

$$\delta_L = [1 + (L^S/L^N)\,[K_A/K_A^*]^{-\nu}\,\vartheta^{\mu}]^{-1}$$

and

$$\delta_Z = [\delta_I - (1-\phi)\delta_L]/\phi.$$

The ratio K_A/K_A^* in trade solves

$$\left[\frac{K_A}{K_A^*}\right]^{\sigma} = \frac{\xi[1-(1-\phi)\Delta(K_A/K_A^*)]-1}{\xi[1-(1-\phi)\Delta(K_A/K_A^*)[K_A/K_A^*]^{-\nu\xi}(L^*/L)\vartheta]-1} \tag{39}$$

where

$$\Delta(k) = \frac{1+(n^*/n)k^{\nu(\xi-1)}\vartheta^{-(1-\mu)}}{1+(L^S/L^N)k^{-\nu}\vartheta^{\mu}}.$$

Proof: see the appendix.

The next three propositions summarize the effect of trade liberalization, i.e. a decrease in ϑ from $\bar{\vartheta}$, on prices in proposition 3, on emissions in proposition 4 and on regional revenues in proposition 5.

Proposition 3 *With the opening of the frontiers*

i/ The discrepancy between emission taxes and national incomes increases if σ is large enough:

$$\frac{d}{d\vartheta}\left[\frac{\tau}{\tau^*}\right]\Bigg|_{\vartheta=\bar{\vartheta}} = \frac{d}{d\vartheta}\left[\frac{I}{I^*}\right]\Bigg|_{\vartheta=\bar{\vartheta}} < 0 \text{ if } \sigma > \bar{\sigma} \equiv 1 + \frac{\phi(1-\mu)}{\mu-\phi}.$$

ii/ The discrepancy between natural capital prices decreases:

$$\frac{d}{d\vartheta}\left[\frac{\tau_A}{\tau_A^*}\right]\Bigg|_{\vartheta=\bar{\vartheta}} > 0.$$

iii/ The discrepancy between wages increases:

$$\frac{d}{d\vartheta}\left[\frac{w}{w^*}\right]\Bigg|_{\vartheta=\bar{\vartheta}} < 0.$$

iv/ The discrepancy between the input price ratios decreases:

$$\frac{d}{d\vartheta}\left[\frac{\tau/w}{\tau^*/w^*}\right]\Bigg|_{\vartheta=\bar{\vartheta}} > 0.$$

Proof: see the appendix.

Both the wage ratio and the emission tax ratio increase (if σ is large enough), although the reduction of trade frictions allows for a reduction of the ratio of relative input prices, which reflects some convergence. Hence the increase in the ratio of emission tax is smaller than the increase in the wage ratio. Surprisingly, the ratios of natural capital prices and of emission taxes evolve in opposite direction. As τ and τ_A are positively related according to (13), this difference must come from a discrepancy in the use of natural capital: the ratio K_A/K_A^* that solves (39) must decrease when ϑ decreases. This is indeed the case, as stated in the following proposition:

Proposition 4 *With the opening of the frontiers, compared to autarky*

i/ Agricultural activities use more natural capital in South and less in North: $K_A^t < K_A^a < K_A^{*t}$.

ii/ Industries pollute more in North and less in South: $Z_M^t > Z_M^a > Z_M^{*t}$.

iii/ Northern total emissions increase whereas Southern ones decrease: $Z^t > Z^a > Z^{*t}$.

iv/ The global level of pollution decreases: $Z^{wt} < Z^{wa}$.

Proof: see the appendix.

At equilibrium, more natural capital is used in South compared to North, which leads to larger GHG emissions due to natural capital in South compared to North. On the opposite, industrial sectors in North pollute more than the Southern ones in trade, resulting in a higher level of emissions from Northern countries than Southern ones. Two countervailing effects lead to this situation. On the one hand, there is a technique effect: Northern industries emit less per unit of good in North, since they use more bioenergy and less fossil energy. On the other hand, there is a strong scale effect: more industrial production takes place in North in trade. As a result, GHG emissions due to industrial production in a Northern country increase (and decrease in South). Since the Southern industries are more pollution intensive than Northern ones (due to environmental policy difference) in autarky, reallocating industries from South to North would reduce pollution while keeping total production constant. However, trade improves the factor allocation and allows to increase the production levels. In Northern countries, the resulting balance of emissions is negative: the rise in production leads to an increase in industrial emissions that surpasses the decrease in emissions from agriculture, resulting in a total level of emissions larger in trade than in autarky. Albeit the fact that GHG emissions generated from the use of natural capital increase rapidly (ψ is convex) and that trade induces a discrepancy in the use of natural capital (while all countries use the same level K_A^a under autarky), trade allows to reduce the total level of emissions. This reduction in global pollution affects positively Northern and Southern consumers' welfare.

The main consequence of an opening of countries to trade is a new sectoral allocation, resulting in an increased pressure on natural capital in the Southern countries. This effect can be interpreted as a cross-sectoral leakage, since trade allows a higher bioenergy requirement in Northern industry, hence a lower pollution intensity per unit of manufacturing good, and as a consequence, it leads to more land use change in South. However, since GHG emissions from agriculture are more taxed than the equivalent industrial emissions by a factor σ ($\tau_A K_A = \sigma \tau Z_A$), the Southern countries cannot let its natural capital use increase dramatically. This Pigovian policy, although resulting from a Nash equilibrium between countries, depends on global pollution levels and results in a welfare sacrifice for South. In fact,

Proposition 5 *With the opening of the frontiers, compared to autarky, the revenue of Northern countries increases provided $\sigma \geq \bar{\sigma}$ whereas the revenue of Southern countries decreases.*

Proof: see the appendix.

Traditionally trade is welfare improving for consumers. However in the presence of a global externality, such as GHG emissions, trade may deteriorate the revenue of one region, due to a trade-off between consumption and environmental quality, as well as to the sub-optimality of a Nash equilibrium (that determines national pollution targets). Consumers' welfare from both regions are increased thanks to the decrease in global pollution. However, the increase in the ratio I^N/I^S due to the opening to trade corresponds to both a rise in Northern revenue and a decrease in Southern revenue. Since

North was already richer in autarky, trade is widening the gap between the two regions. This outcome is made possible by the fact that trade does not equalize factor prices, due to the presence of an intermediate good. For Southern consumers, trade impacts on their welfare depend on β, the weight of pollution harm relative to consumption of goods in the utility function. If β is sufficiently high, the decrease in global pollution will more than compensate the loss of revenue. However, the revenue deterioration impact of trade makes a very strong case against trade liberalization or international agreements on climate policies for Southern countries.

To test whether the impacts of trade liberalization are still observed in the free-trade situation, we reduce the trade barriers to zero ($\vartheta = 1$). Due to computational difficulties, the demonstration is not tractable for many of the previous propositions, but the directions of trade and the pollution changes are the same. The following proposition characterizes the free-trade situation:

Proposition 6 *Under diversified free trade, when L^*/L is not too small*

i/ Southern agricultural sector emits more than Northern one.

ii/ Northern industries pollute more than Southern ones.

iii/ Northern countries pollute more than Southern ones.

iv/ $\tau/w > \tau^*/w^*$

Proof: see the appendix.

Hence, contrary to Heckscher-Ohlin-Samuelson theory where, in a two-good, two-factor framework, trade is characterized by the equalization of factor prices, we obtain different factor prices in trade. In fact, $K_A^{*t} > K_A^t$ leads to $w < w^*$ and $\tau > \tau^*$. This result can be explained by the presence of three factors for two goods as illustrated in Fig. 2. The industrial iso-cost curves are identical across regions, whereas, for agriculture, the Southern iso-cost curve is lower than the Northern one since the amount of natural capital is higher. Since $K_A^{*t} > K_A^t$, the level of agricultural emissions in South is higher than in North. Given (19), we have $\mu\xi(Z_M^t - Z_M^{*t}) = \sigma(Z_A^{*t} - Z_A^t)$, hence, industrial emissions in North are higher than in South. As $\sigma > \mu\xi$ under (17), we have $Z_M^t - Z_M^{*t} > Z_A^{*t} - Z_A^t$ which explains that Northern countries are the more polluting ones. There is a strong inertia in the agricultural sector where the optimal tax per unit of emission allows for a lower variation in emissions than in the industrial sector, hence a smaller discrepancy between regions.

5 Conclusion

Contrary to Copeland and Taylor (1995), in the context of no factor price equalization, trade of commodities and bioenergy has a beneficial impact on the environment since the level of global pollution is reduced compared to autarky. This is due to a technique effect of trade since the Northern countries concentrate most of the industrial production and use more bioenergy intensive techniques. Considering the environment only through the GHG emissions allows us to conclude on the positive impact of trade. This view, however, excludes other aspects of land use change, and we should keep in mind that the increase in natural capital use in South is responsible for biodiversity loss, soil erosion and ecosystem disturbances. These impacts are not explicitly considered in our model, but the higher per unit emission tax in the agricultural sector compare to the industrial sector reflects the higher damages of land use changes.

Furthermore, a diversified trade equilibrium leading to a more industrialized North and to a more resource dependent South has an impact on welfare that differs from one region to the other. The optimal taxes that regulate GHG emissions in both sectors depend on the global level of emissions and are stricter for the agricultural sector. As a consequence, the Southern countries are not able to benefit from trade, except for the reduction in global pollution. The Southern countries experience a decrease in their revenue, whereas the Northern countries benefit from trade. This makes a strong case against the Southern countries' involvement in international agreements that would result in more demanding environmental policy than the one freely decided in the absence of coordination, such as binding targets of emissions reduction in a future post-Kyoto framework.

Appendix

A Proof of Lemma 2

The shares $\delta_I, \delta_L, \delta_Z$ are obtained using (12), (28), (29), (27), (26) and $\delta_I = \phi\delta_Z + (1-\phi)\delta_L$. We have

$$\frac{\delta_L}{\delta_I} = \frac{1+(n^*/n)(\tau^*/\tau)}{1+(L^S/L^N)(w^*/w)} = \frac{1+(n^*/n)\left[K_A/K_A^*\right]^{\nu(\xi-1)}\vartheta^{-(1-\mu)}}{1+(L^S/L^N)\left[K_A/K_A^*\right]^{-\nu}\vartheta^{\mu}} = \Delta(K_A/K_A^*). \tag{40}$$

Symmetrically, $\phi(1-\delta_Z)/(1-\delta_I) = 1-(1-\phi)(1-\delta_L)/(1-\delta_I)$ where

$$\frac{1-\delta_L}{1-\delta_I} = \frac{(L^S/L^N)\left[K_A/K_A^*\right]^{-\nu}}{(n^*/n)\left[K_A/K_A^*\right]^{\nu(\xi-1)}}\vartheta\frac{\delta_L}{\delta_I} = (L^*/L)\left[K_A/K_A^*\right]^{-\nu\xi}\vartheta\Delta(K_A/K_A^*) \tag{41}$$

These two equations lead to (39), using (34) and (36).

B Proof of Propositions 3 and 4

To determine the impact of a change of trade friction on the Northern and Southern pollution shares, we need to evaluate the derivatives of the different pollution levels wrt ϑ at $K_A = K_A^*$ and $\vartheta = \bar{\vartheta} = \ell^{-1}$, where $\ell \equiv L^*/L$. For all $\vartheta \in [0, \bar{\vartheta}]$, (39) can be expressed as $\Psi(K_A/K_A^*, \vartheta) = 0$ where

$$\Psi(k,\vartheta) \equiv k^{\sigma} - g(k,\vartheta)$$

with

$$g(k,\vartheta) = \frac{\xi - 1 - f(k,\vartheta)}{\xi - 1 - f(k,\vartheta)k^{-\nu\xi}\ell\vartheta}$$

and

$$f(k,\vartheta) = \xi(1-\phi)\frac{1+(n^*/n)k^{\nu(\xi-1)}\vartheta^{-(1-\mu)}}{1+(n^*/n)\ell k^{-\nu}\vartheta^{\mu}}.$$

Consequently, $K_A/K_A^* = \tilde{k}(\vartheta)$ where $\tilde{k}(\vartheta)$ is a function satisfying $\tilde{k}(\bar{\vartheta}) = 1$ and, using the implicit function theorem,

$$\tilde{k}'(\vartheta) = \frac{\partial g(\tilde{k}(\vartheta),\vartheta)/\partial\vartheta}{\sigma\tilde{k}(\vartheta)^{\sigma-1} - \partial g(\tilde{k}(\vartheta),\vartheta)/\partial k}.$$

We have

$$\frac{\partial g(k,\vartheta)}{\partial \vartheta} = -\frac{\partial f(k,\vartheta)}{\partial \vartheta}\frac{(\xi-1)(1-k^{-\nu\xi}\ell\vartheta)}{[\xi-1-f(k,\vartheta)k^{-\nu\xi}\ell\vartheta]^2} + \frac{f(k,\vartheta)k^{-\nu\xi}\ell g(k,\vartheta)}{\xi-1-f(k,\vartheta)k^{-\nu\xi}\ell\vartheta}$$

and

$$\frac{\partial g(k,\vartheta)}{\partial k} = -\frac{\partial f(k,\vartheta)}{\partial k}\frac{(\xi-1)(1-k^{-\nu\xi}\ell\vartheta)}{[\xi-1-f(k,\vartheta)k^{-\nu\xi}\ell\vartheta]^2} - \frac{\nu\xi f(k,\vartheta)k^{-(\nu\xi+1)}\ell\vartheta g(k,\vartheta)}{\xi-1-f(k,\vartheta)k^{-\nu\xi}\ell\vartheta}.$$

Simple computations give

$$\frac{\partial f(1,\bar\vartheta)}{\partial \vartheta} = -\frac{(n^*/n)\ell^{2-\mu}\xi(1-\phi)}{1+(n^*/n)\ell^{1-\mu}}, \frac{\partial f(1,\bar\vartheta)}{\partial k} = \frac{(n^*/n)\ell^{1-\mu}\nu\xi^2(1-\phi)}{1+(n^*/n)\ell^{1-\mu}}$$

and $f(1,\bar\vartheta)=\xi(1-\phi)$ and $g(1,\bar\vartheta)=1$. We thus get

$$\frac{\partial g(1,\bar\vartheta)}{\partial \vartheta} = \frac{\xi(1-\phi)\ell}{\xi\phi-1}, \frac{\partial g(1,\bar\vartheta)}{\partial k} = -\frac{\nu\xi^2(1-\phi)}{\xi\phi-1}$$

where

$$\xi\phi-1=(\xi\mu-1)[1-(1-e\alpha)b_M]>0.$$

Consequently

$$\tilde k'(\bar\vartheta) = \frac{\xi(1-\phi)\ell}{\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)}>0.$$

Hence, $\tilde k(\bar\vartheta-d\vartheta)\approx \tilde k(\bar\vartheta)-d\vartheta\tilde k'(\bar\vartheta)<\tilde k(\bar\vartheta)=1$. By definition, $\delta_L/\delta_I = f(\tilde k(\vartheta),\vartheta)/[\xi(1-\phi)]$ and we have

$$\frac{df(\tilde k(\bar\vartheta),\bar\vartheta)}{d\vartheta} = -\frac{(1-\phi)(n^*/n)\xi\ell^{2-\mu}\sigma(\xi\phi-1)}{[1+(n^*/n)\ell^{1-\mu}]\left[\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)\right]}<0.$$

Consequently

$$\frac{d}{d\vartheta}\left[\frac{\delta_L}{\delta_I}\right]\Big|_{\vartheta=\bar\vartheta} = -\frac{(n^*/n)\ell^{2-\mu}\sigma(\xi\phi-1)}{[1+(n^*/n)\ell^{1-\mu}]\left[\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)\right]}<0, \quad (42)$$

$$\frac{d}{d\vartheta}\left[\frac{1-\delta_L}{1-\delta_I}\right]\Big|_{\vartheta=\bar\vartheta} = \frac{\ell\sigma(\xi\phi-1)}{[1+(n^*/n)\ell^{1-\mu}]\left[\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)\right]}>0. \quad (43)$$

Furthermore, since

$$Z^{wt} = \left\{\frac{(n+n^*)[\mu(\sigma-1)+\mu\xi-\sigma]-(1-\phi)(\mu\xi-\sigma)[n\frac{\delta_L}{\delta_I}+n^*\frac{1-\delta_L}{1-\delta_I}]}{\sigma\beta(\mu\xi-1)}\right\}^{1/\gamma},$$

and $Z^{wa} = \{(n+n^*)[\mu(\sigma-1)+\phi(\mu\xi-\sigma)]/[\sigma\beta(\mu\xi-1)]\}^{1/\gamma}$, which is positive since $\mu(\sigma-1)+\phi(\mu\xi-\sigma) = (\mu\xi-1)[\mu-(\mu\xi-\sigma)(1-e)\alpha b_M] > 0$, we obtain

$$\begin{aligned}\left.\frac{dZ^{wt}}{d\vartheta}\right|_{\vartheta=\bar{\vartheta}} &= -\frac{(1-\phi)(\mu\xi-\sigma)}{\sigma\beta\gamma(\mu\xi-1)}\ \frac{d}{d\vartheta}\left.\left[n\frac{\delta_L}{\delta_I}+n^*\frac{1-\delta_L}{1-\delta_I}\right]\right|_{\vartheta=\bar{\vartheta}}(Z^{wa})^{1-\gamma} \\ &= \frac{n^*(1-\phi)(\mu\xi-\sigma)\sigma(\xi\phi-1)\ell\left[\ell^{1-\mu}-1\right](Z^{wa})^{1-\gamma}}{\sigma\beta\gamma(\mu\xi-1)\left[1+(n^*/n)\ell^{1-\mu}\right]\left[\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)\right]},\quad (44)\end{aligned}$$

which is positive since $\ell < 1$ and $\mu\xi < \sigma$. As $\phi\delta_Z/\delta_I = 1-(1-\phi)\delta_L/\delta_I$, Z_M, Z and Z_A^* are unambiguously decreasing with ϑ at $\vartheta = \bar{\vartheta}$. Using (36), we get

$$\begin{aligned}\left.\frac{dZ_M^*}{d\vartheta}\right|_{\vartheta=\bar{\vartheta}} &= \frac{1}{(\mu\xi-1)\beta}\left.\left[(1-\phi)\frac{d}{d\vartheta}\left[\frac{1-\delta_L}{1-\delta_I}\right](Z^{wa})^{1-\gamma}-\frac{(\gamma-1)(\mu-\phi)}{(Z^{wa})^{\gamma}}\frac{dZ^{wt}}{d\vartheta}\right]\right|_{\vartheta=\bar{\vartheta}} \\ &= \frac{(1-\phi)(Z^{wa})^{1-\gamma}}{(\mu\xi-1)\beta}\left[1-n^*\frac{(\gamma-1)(\mu-\phi)(\mu\xi-\sigma)[\ell^{1-\mu}-1]}{\sigma\beta\gamma(\mu\xi-1)(Z^{wa})^{\gamma}}\right]\frac{d}{d\vartheta}\left.\left[\frac{1-\delta_L}{1-\delta_I}\right]\right|_{\vartheta=\bar{\vartheta}},\end{aligned}$$

which is positive, since $\mu\xi < \sigma$ and $\phi = \mu-(\mu\xi-1)(1-e)\alpha b_M < \mu$ and $\ell < 1$, provided

$$\begin{gathered}\sigma\beta(\mu\xi-1)(Z^{wa})^{\gamma} > n^*(\mu-\phi)(\sigma-\mu\xi)[1-\ell^{1-\mu}] \\ \frac{\mu(\sigma-1)-\phi(\sigma-\mu\xi)}{(\mu-\phi)(\sigma-\mu\xi)[1-\ell^{1-\mu}]} > \frac{n^*}{n+n^*}\end{gathered}$$

As $n^*/(n+n^*)$ is bounded by one, it suffices that the LHT is greater than 1 for $(dZ_M^*/d\vartheta)|_{\vartheta=\bar{\vartheta}} > 0$. Obviously, the LHT diverges when $\ell \to 1$. For low ℓ, the LHT is bounded below by $[\mu(\sigma-1)-\phi(\sigma-\mu\xi)]/[(\mu-\phi)(\sigma-\mu\xi)]$, which is greater than 1 given H2.

Using (37), we get

$$\begin{aligned}\left.\frac{dZ^*}{d\vartheta}\right|_{\vartheta=\bar{\vartheta}} &= \frac{-(1-\phi)(\mu\xi-\sigma)(Z^{wa})^{1-\gamma}}{(\mu\xi-1)\sigma\beta}\ \frac{d}{d\vartheta}\left.\left[\frac{1-\delta_L}{1-\delta_I}\right]\right|_{\vartheta=\bar{\vartheta}} \\ &\quad -\frac{(\gamma-1)\left[\mu(\sigma-1)+\phi(\mu\xi-\sigma)\right]}{(\mu\xi-1)\sigma\beta(Z^{wa})^{\gamma}}\ \left.\frac{dZ^{wt}}{d\vartheta}\right|_{\vartheta=\bar{\vartheta}} \\ &= \frac{-(\mu\xi-\sigma)(1-\phi)(Z^{wa})^{1-\gamma}}{(\mu\xi-1)\sigma\beta}\ \frac{d}{d\vartheta}\left.\left[\frac{1-\delta_L}{1-\delta_I}\right]\right|_{\vartheta=\bar{\vartheta}} \\ &\quad\times\left[1-n^*\frac{(\gamma-1)\left[\mu(\sigma-1)+\phi(\mu\xi-\sigma)\right]\left[1-\ell^{1-\mu}\right]}{\sigma\beta\gamma(\mu\xi-1)(Z^{wa})^{\gamma}}\right],\end{aligned}$$

which is also positive provided that

$$\sigma\beta\gamma(\mu\xi-1)(Z^{wa})^{\gamma} > n^*(\gamma-1)\left[\mu(\sigma-1)+\phi(\mu\xi-\sigma)\right]\left[1-\ell^{1-\mu}\right]$$
$$\frac{\gamma}{(\gamma-1)[1-\ell^{1-\mu}]} > \frac{n^*}{n+n^*}$$

Since $n^*/(n+n^*) < 1$, the inequality holds if the LHT is greater than 1. Obviously, the LHT diverges when $\ell \to 1$. For low ℓ, the LHT is bounded below by $\gamma/(\gamma-1) > 1$.

Finally, using (34), we have

$$\begin{aligned}\left.\frac{dZ_A}{d\vartheta}\right|_{\vartheta=\bar{\vartheta}} &= \frac{-\mu\xi(1-\phi)(Z^{wa})^{1-\gamma}}{(\mu\xi-1)\sigma\beta}\left.\frac{d}{d\vartheta}\left[\frac{\delta_L}{\delta_I}\right]\right|_{\vartheta=\bar{\vartheta}} - \mu\frac{(\gamma-1)\left[\xi\phi-1\right]}{(Z^{wa})^{\gamma}(\mu\xi-1)\sigma\beta}\left.\frac{dZ^{wt}}{d\vartheta}\right|_{\vartheta=\bar{\vartheta}} \\ &= \frac{\mu(1-\phi)(Z^{wa})^{1-\gamma}}{(\mu\xi-1)\sigma\beta}\left[-\xi+n(\gamma-1)\frac{(\mu\xi-\sigma)(\xi\phi-1)[\ell^{1-\mu}-1]}{\sigma\beta(\mu\xi-1)\ell^{1-\mu}(Z^{wa})^{\gamma}}\right]\left.\frac{d}{d\vartheta}\left[\frac{\delta_L}{\delta_I}\right]\right|_{\vartheta=\bar{\vartheta}},\end{aligned}$$

which is positive, since $d[\delta_L/\delta_I]/d\vartheta < 0$ and $\mu\xi < \sigma$, provided that

$$\sigma\beta\gamma\xi(\mu\xi-1)(Z^{wa})^{\gamma} > n(\gamma-1)(\xi\phi-1)(\sigma-\mu\xi)[\ell^{\mu-1}-1]$$
$$\frac{\gamma\xi\left[\mu(\sigma-1)+\phi(\mu\xi-\sigma)\right]}{(\gamma-1)(\xi\phi-1)(\sigma-\mu\xi)[\ell^{\mu-1}-1]} > \frac{n}{n+n^*}$$

which holds if $\ell \to 1$ but which is not verified when $\ell \to 0$ since the RHS diverges.

Using (26) and (27), we have

$$\frac{\tau/w}{\tau^*/w^*} = \tilde{k}(\vartheta)^{-\nu\xi}\vartheta$$

and thus

$$\left.\frac{d}{d\vartheta}\left[\frac{\tau/w}{\tau^*/w^*}\right]\right|_{\vartheta=\bar{\vartheta}} = \left[\frac{1}{\bar{\vartheta}} - \frac{\nu\xi\tilde{k}'(\bar{\vartheta})}{\tilde{k}(\bar{\vartheta})}\right]\left.\frac{\tau/w}{\tau^*/w^*}\right|_{\vartheta=\bar{\vartheta}}$$

where

$$\frac{1}{\bar{\vartheta}} - \frac{\nu\xi\tilde{k}'(\bar{\vartheta})}{\tilde{k}(\bar{\vartheta})} = \frac{\ell\sigma(\xi\phi-1)}{\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)} > 0$$

Similar computations using (26) give

$$\left.\frac{d}{d\vartheta}\left[\frac{\tau}{\tau^*}\right]\right|_{\vartheta=\bar{\vartheta}} = \left[\frac{1-\mu}{\bar{\vartheta}} - \frac{\nu(\xi-1)\tilde{k}'(\bar{\vartheta})}{\tilde{k}(\bar{\vartheta})}\right]\left.\frac{\tau}{\tau^*}\right|_{\vartheta=\bar{\vartheta}}.$$

As

$$\frac{1-\mu}{\bar{\vartheta}} - \frac{\nu(\xi-1)\tilde{k}'(\bar{\vartheta})}{\tilde{k}(\bar{\vartheta})} = \frac{(1-\mu)\sigma(\xi\phi-1) - \mu\xi(\sigma-1)(1-\phi)}{\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)}\ell$$

where

$$(1-\mu)\sigma(\xi\phi-1) - \mu\xi(\sigma-1)(1-\phi) = -\{\xi(\mu-\phi)(\sigma-\bar{\sigma}) + (1-\mu)\sigma\}$$

is always negative when $\sigma \geq \bar{\sigma} \equiv 1+\phi(1-\mu)/(\mu-\phi)$, we have $(d/d\vartheta)\left[\tau/\tau^*\right]|_{\vartheta=\bar{\vartheta}} < 0$ if $\sigma > \bar{\sigma}$. Using (13), we have

$$\frac{\tau_A}{\tau_A^*} = \tilde{k}(\vartheta)^{\sigma-1}\frac{\tau}{\tau^*}$$

and thus

$$\frac{d}{d\vartheta}\left[\frac{\tau_A}{\tau_A^*}\right]\Bigg|_{\vartheta=\bar{\vartheta}} = \left[(\sigma-1)\frac{\tilde{k}'(\bar{\vartheta})}{\tilde{k}(\bar{\vartheta})} + \frac{1-\mu}{\bar{\vartheta}} - \frac{\nu(\xi-1)\tilde{k}'(\bar{\vartheta})}{\tilde{k}(\bar{\vartheta})}\right]\frac{\tau_A}{\tau_A^*}\Bigg|_{\vartheta=\bar{\vartheta}}$$

where

$$(\sigma-1)\frac{\tilde{k}'(\bar{\vartheta})}{\tilde{k}(\bar{\vartheta})} + \frac{1-\mu}{\bar{\vartheta}} - \frac{\nu(\xi-1)\tilde{k}'(\bar{\vartheta})}{\tilde{k}(\bar{\vartheta})} = \frac{(1-\mu)[\sigma(\xi\phi-1)+(\sigma-1)\xi(1-\phi)]}{\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)}\ell > 0$$

Finally, using (27), we get

$$\frac{d}{d\vartheta}\left[\frac{w}{w^*}\right]\Bigg|_{\vartheta=\bar{\vartheta}} = \left[\frac{\nu\tilde{k}'(\bar{\vartheta})}{\tilde{k}(\bar{\vartheta})} - \frac{\mu}{\bar{\vartheta}}\right]\frac{w}{w^*}\Bigg|_{\vartheta=\bar{\vartheta}}$$

where

$$\nu\tilde{k}'(\bar{\vartheta})/\tilde{k}(\bar{\vartheta}) - \mu/\bar{\vartheta} = -\frac{\nu\xi(1-\phi)(\mu\xi-1)+\mu\sigma(\xi\phi-1)}{\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)}\ell < 0.$$

C Proof of Proposition 5

Using (14) and (32) we get

$$\frac{\tau}{w} = \frac{L\beta(Z^w)^{\gamma-1}}{(1-\phi)\delta_L/\delta_I} = \frac{L\beta(Z^w)^{\gamma-1}}{1-\phi\delta_Z/\delta_I}. \quad (45)$$

Using (18) and (32) yields

$$\frac{L_A}{L} = \frac{1-\mu}{\mu}\frac{\sigma Z_A\beta(Z^w)^{\gamma-1}}{1-\phi\delta_Z/\delta_I}$$

which, combined with (34), gives

$$\frac{L_A}{L} = \frac{1-\mu}{\mu\xi-1}\frac{\xi\phi\delta_Z/\delta_I-1}{1-\phi\delta_Z/\delta_I}.$$

Since, by definition, $A/L_A = K_A^{\mu}L_A^{-\mu}$ and $K_A = [\sigma Z_A/\lambda]^{1/\sigma}$, combining the expression of L_A/L with (5) and (34) gives

$$\begin{aligned} w &= (1-\mu)\left[\frac{\mu(\xi\phi\delta_Z/\delta_I-1)}{\lambda(\mu\xi-1)\beta(Z^w)^{\gamma-1}}\right]^{\mu/\sigma}\left[\frac{1-\mu}{\mu\xi-1}\frac{\xi\phi\delta_Z/\delta_I-1}{1-\phi\delta_Z/\delta_I}L\right]^{-\mu} \\ &= \frac{(1-\mu)^{1-\mu}(\mu\xi-1)^{\mu(1-1/\sigma)}(\mu/\lambda)^{\mu/\sigma}(1-\phi\delta_Z/\delta_I)^{\mu}}{L^{\mu}(\xi\phi\delta_Z/\delta_I-1)^{\mu(\sigma-1)/\sigma}\left[\beta(Z^w)^{\gamma-1}\right]^{\mu/\sigma}}, \end{aligned}$$

and using (45)

$$\tau = \frac{(1-\mu)^{1-\mu}(\mu\xi-1)^{\mu(1-1/\sigma)}(\mu/\lambda)^{\mu/\sigma}L^{1-\mu}\left[\beta(Z^w)^{\gamma-1}\right]^{1-\mu/\sigma}}{(\xi\phi\delta_Z/\delta_I-1)^{\mu(\sigma-1)/\sigma}(1-\phi\delta_Z/\delta_I)^{1-\mu}}.$$

Finally, using (12), we obtain for a Northern country

$$\begin{aligned} I &= \frac{\tau}{\beta(Z^w)^{\gamma-1}} = \frac{(1-\mu)^{1-\mu}(\mu\xi-1)^{\mu(1-1/\sigma)}(\mu/\lambda)^{\mu/\sigma}L^{1-\mu}}{\left[\beta(Z^w)^{\gamma-1}\right]^{\mu/\sigma}(\xi\phi\delta_Z/\delta_I-1)^{\mu(\sigma-1)/\sigma}(1-\phi\delta_Z/\delta_I)^{1-\mu}} \\ &= \frac{(1-\mu)^{1-\mu}(\mu\xi-1)^{\mu(1-1/\sigma)}(\mu/\lambda)^{\mu/\sigma}L^{1-\mu}}{\left[\beta(Z^w)^{\gamma-1}\right]^{\mu/\sigma}m(\phi\delta_Z/\delta_I)} \end{aligned}$$

and thus

$$I^* = \frac{(1-\mu)^{1-\mu}(\mu\xi-1)^{\mu(1-1/\sigma)}(\mu/\lambda)^{\mu/\sigma}L^{*1-\mu}}{\left[\beta(Z^w)^{\gamma-1}\right]^{\mu/\sigma}m(\phi(1-\delta_Z)/(1-\delta_I))} \tag{46}$$

for a Southern country, where

$$m(x) \equiv [\xi x-1]^{\mu(\sigma-1)/\sigma}[1-x]^{1-\mu}$$

is a convex function with $m(x) > 0$ iff $x \in (1/\xi, 1)$ with $m(1/\xi) = m(1) = 0$. Using

$$m'(x) = m(x)\frac{\xi\mu(\sigma-1)(1-x)-(1-\mu)\sigma(\xi x-1)}{\sigma(\xi x-1)(1-x)}$$

we have $m'(\phi) > 0$ if $\sigma > \bar{\sigma}$. As

$$\frac{d}{d\vartheta}\left[\frac{\delta_Z}{\delta_I}\right]\Big|_{\vartheta=\bar{\vartheta}} = -\frac{1-\phi}{\phi}\frac{d}{d\vartheta}\left[\frac{\delta_L}{\delta_I}\right]\Big|_{\vartheta=\bar{\vartheta}} > 0$$

$$\frac{d}{d\vartheta}\left[\frac{1-\delta_Z}{1-\delta_I}\right]\Bigg|_{\vartheta=\bar{\vartheta}} = -\frac{1-\phi}{\phi}\frac{d}{d\vartheta}\left[\frac{1-\delta_L}{1-\delta_I}\right]\Bigg|_{\vartheta=\bar{\vartheta}} < 0$$

and $(dZ^{wt}/d\vartheta)\big|_{\vartheta=\bar{\vartheta}} > 0$, we thus have $(dI/d\vartheta)|_{\vartheta=\bar{\vartheta}} < 0$ if $\sigma > \bar{\sigma}$.

Differentiating the denominator of (46), we obtain for the impact on Southern revenue

$$\begin{aligned} & \left[\beta(Z^{wa})^{\gamma-1}\right]^{\frac{\mu}{\sigma}}\left\{\frac{(\gamma-1)\mu(Z^{wa})^{-1}}{\sigma}\frac{dZ^{wt}}{d\vartheta}\bigg|_{\vartheta=\bar{\vartheta}} m(\phi) + m'(\phi)\phi\frac{d}{d\vartheta}\left[\frac{1-\delta_Z}{1-\delta_I}\right]\bigg|_{\vartheta=\bar{\vartheta}}\right\} \\ = \; & m(\phi)\left[\beta(Z^{wa})^{\gamma-1}\right]^{\mu/\sigma}\left\{\frac{(\gamma-1)\mu}{\sigma}(Z^{wa})^{-1}\frac{dZ^{wt}}{d\vartheta}\bigg|_{\vartheta=\bar{\vartheta}}\right. \\ & \left. -\frac{\xi\mu(\sigma-1)(1-\phi)-(1-\mu)\sigma(\xi\phi-1)}{\sigma(\xi\phi-1)}\frac{d}{d\vartheta}\left[\frac{1-\delta_L}{1-\delta_I}\right]\bigg|_{\vartheta=\bar{\vartheta}}\right\} \end{aligned}$$

Using (43) and (44), the first bracketed term simplifies to

$$\begin{aligned} & \frac{(\gamma-1)\mu n^*(1-\phi)(\mu\xi-\sigma)(\xi\phi-1)\ell\left[\ell^{1-\mu}-1\right](Z^{wa})^{-\gamma}}{\sigma\beta\gamma(\mu\xi-1)\left[1+(n^*/n)\ell^{1-\mu}\right]\left[\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)\right]} \\ = \; & \frac{n^*}{(n+n^*)[\mu(\sigma-1)+\phi(\mu\xi-\sigma)]}\frac{(\gamma-1)\mu(1-\phi)(\mu\xi-\sigma)(\xi\phi-1)\ell\left[\ell^{1-\mu}-1\right]}{\gamma\left[1+(n^*/n)\ell^{1-\mu}\right]\left[\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)\right]} \end{aligned}$$

and the second to

$$\frac{\ell\{\xi\mu(\sigma-1)(1-\phi)-(1-\mu)\sigma(\xi\phi-1)\}}{\left[1+(n^*/n)\ell^{1-\mu}\right]\left[\sigma(\xi\phi-1)+\nu\xi^2(1-\phi)\right]}.$$

Hence $(dI^*/d\vartheta)|_{\vartheta=\bar{\vartheta}}$ has the sign of

$$\begin{aligned} & -(\gamma-1)\mu n^*(1-\phi)(\mu\xi-\sigma)(\xi\phi-1)\left[\ell^{1-\mu}-1\right] \\ & +\gamma(n+n^*)[\mu(\sigma-1)+\phi(\mu\xi-\sigma)]\{\xi\mu(\sigma-1)(1-\phi)-(1-\mu)\sigma(\xi\phi-1)\} \end{aligned}$$

which is positive when

$$\frac{n^*}{n+n^*} < \frac{\gamma[\mu(\sigma-1)+\phi(\mu\xi-\sigma)]\{\xi(\mu-\phi)(\sigma-\bar{\sigma})+(1-\mu)\sigma\}}{(\gamma-1)\mu(1-\phi)(\sigma-\mu\xi)(\xi\phi-1)(1-\ell^{1-\mu})}.$$

As $n^*/(n+n^*)$ is bounded by one, it suffices that the RHT is greater than 1 for $(dI^*/d\vartheta)|_{\vartheta=\bar{\vartheta}} > 0$. Obviously, the RHT diverges when $\ell \to 1$. For low ℓ, the RHT is bounded below by

$$\frac{\gamma[\mu(\sigma-1)+\phi(\mu\xi-\sigma)]\{\xi(\mu-\phi)(\sigma-\bar{\sigma})+(1-\mu)\sigma\}}{(\gamma-1)\mu(1-\phi)(\sigma-\mu\xi)(\xi\phi-1)}.$$

This lower bound is greater than 1 provided that

$$[\mu(\sigma-1)+\phi(\mu\xi-\sigma)]\{\mu\xi(\sigma-1)(1-\phi)-(1-\mu)\sigma(\xi\phi-1)\}>\mu(1-\phi)(\sigma-\mu\xi)(\xi\phi-1),$$

as $1-\phi>1-\mu$, it suffices that

$$[\mu(\sigma-1)+\phi(\mu\xi-\sigma)]\{\mu\xi(\sigma-1)-\sigma(\xi\phi-1)\}>\mu(\sigma-\mu\xi)(\xi\phi-1),$$

which can be restated as

$$[\mu(\sigma-1)+\phi(\mu\xi-\sigma)]\sigma\xi(\mu-\phi)>(\sigma-\mu\xi)\sigma(\phi-\mu).$$

As the RHS of the inequality is negative whereas the LHS is positive, the inequality always holds and we have $(dI^*/d\vartheta)|_{\vartheta=\bar{\vartheta}}>0$.

Furthermore, $\tau^*=\beta I^*(Z^w)^{\gamma-1}$ can be restated as

$$\tau^*=\frac{(1-\mu)^{1-\mu}(\mu\xi-1)^{\mu(1-1/\sigma)}(\mu/\lambda)^{\mu/\sigma}(L^*)^{1-\mu}\left[\beta(Z^w)^{\gamma-1}\right]^{\frac{\sigma-\mu}{\sigma}}}{m(\phi(1-\delta_Z)/(1-\delta_I))},$$

which is increasing in ϑ (when $\vartheta=\bar{\vartheta}$) provided $\sigma>\bar{\sigma}$.

$$w=\frac{(1-\mu)^{1-\mu}(\mu\xi-1)^{\mu(1-1/\sigma)}(\mu/\lambda)^{\mu/\sigma}(1-\phi\delta_Z/\delta_I)^{\mu}}{L^{\mu}(\xi\phi\delta_Z/\delta_I-1)^{\mu(\sigma-1)/\sigma}\left[\beta(Z^w)^{\gamma-1}\right]^{\mu/\sigma}}, \tag{47}$$

which is decreasing in ϑ (when $\vartheta=\bar{\vartheta}$) if $\sigma>\bar{\sigma}$. However, the signs of $(dw^*/d\vartheta)|_{\vartheta=\bar{\vartheta}}$ and of $(d\tau/d\vartheta)|_{\vartheta=\bar{\vartheta}}$ are ambiguous when $\sigma>\bar{\sigma}$.

D Proof of Proposition 6

Without trade frictions, we have $\vartheta=1$ and (39) can be expressed as $\Omega(K_A/K_A^*,L^*/L)=0$ where

$$\Omega(k,\ell)\equiv k^{\sigma}-\hat{g}(k,\ell)$$

with

$$\hat{g}(k,\ell)=\frac{\xi-1-\hat{f}(k,\ell)}{\xi-1-\hat{f}(k,\ell)k^{-\nu\xi}\ell}$$

and

$$\hat{f}(k,\ell)=\xi(1-\phi)\frac{1+(n^*/n)k^{\nu(\xi-1)}}{1+(n^*/n)\ell/k^{\nu}}.$$

Consequently, $K_A/K_A^*=\hat{k}(L^*/L)$ where $\hat{k}(\ell)$ is a function satisfying $\hat{k}(1)=1$ (since $\Omega(1,1)=0$) and, using the implicit function theorem,

$$\hat{k}'(\ell)=\frac{\partial\hat{g}(\hat{k}(\ell),\ell)/\partial\ell}{\sigma\hat{k}(\ell)^{\sigma-1}-\partial\hat{g}(\hat{k}(\ell),\ell)/\partial k}.$$

We obtain

$$\frac{\partial \hat{f}(k,\ell)}{\partial \ell} < 0, \frac{\partial \hat{f}(k,\ell)}{\partial k} > 0$$

and

$$\frac{\partial \hat{g}(k,\ell)}{\partial \ell} = -\frac{\partial \hat{f}(k,\ell)}{\partial \ell} \frac{(\xi-1)(1-k^{-\nu\xi}\ell)}{[\xi-1-\hat{f}(k,\ell)k^{-\nu\xi}\ell]^2} + \frac{\hat{f}(k,\ell)k^{-\nu\xi}\hat{g}(k,\ell)}{\xi-1-\hat{f}(k,\ell)k^{-\nu\xi}\ell}$$

where $\xi - 1 = (1-\alpha)/[(1-e)\alpha] > 0$, $\xi - 1 - \hat{f}(k,\ell)k^{-\nu\xi}\ell > 0$ (to have $\psi(K_A^*) \geq 0$) and

$$\frac{\partial \hat{g}(k,\ell)}{\partial k} = -\frac{\partial \hat{f}(k,\ell)}{\partial k} \frac{(\xi-1)(1-k^{-\nu\xi}\ell)}{[\xi-1-\hat{f}(k,\ell)k^{-\nu\xi}\ell]^2} - \frac{\nu\xi\hat{f}(k,\ell)k^{-\nu(\xi+1)}\ell\hat{g}(k,\ell)}{\xi-1-\hat{f}(k,\ell)k^{-\nu\xi}\ell}.$$

In particular, we have $\partial\hat{g}(k,\ell)/\partial\ell > 0$ and $\partial\hat{g}(k,\ell)/\partial k < 0$ whenever $k^{\nu\xi} \geq \ell$. As $\hat{k}(1) = 1$ and $\hat{k}'(1) > 0$, we thus have $K_A/K_A^* = \hat{k}(L^*/L) < \hat{k}(1) = 1$ provided L^*/L is close to 1.

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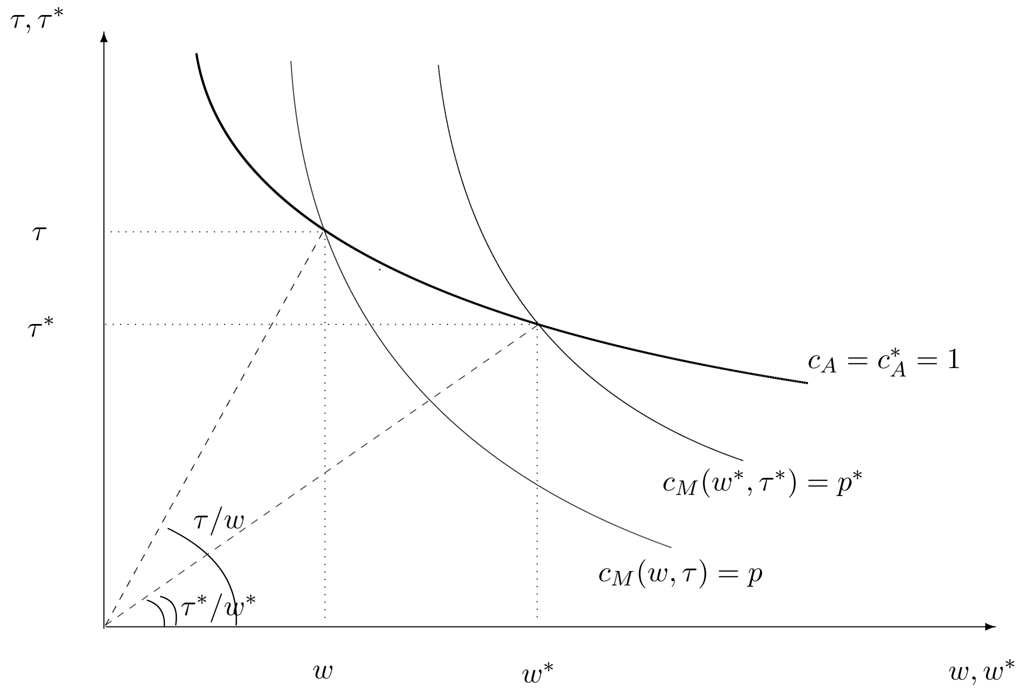

Figure 1: Factor prices under autarky.

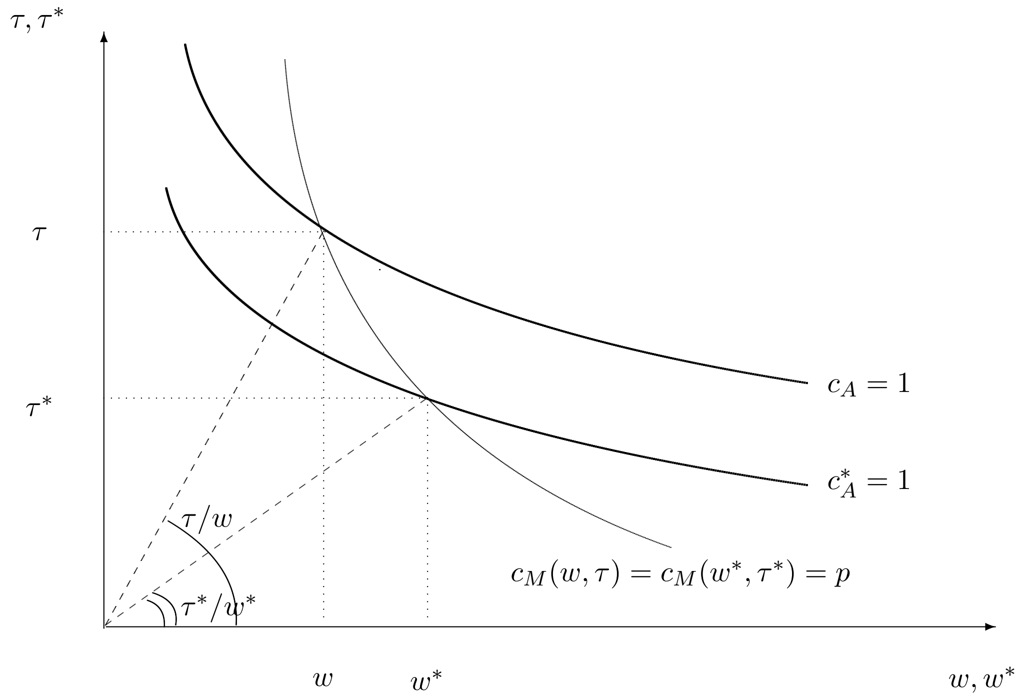

Figure 2: Factor prices under free trade.