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Food trade, Biodiversity Effects and Price Volatility

Cecilia Bellora & Jean-Marc Bourgeon

Highlights

- Inducing agricultural specialisation, trade reduces crop biodiversity and therefore increases agricultural production risks due to biotic factors (pests) and decreases productivity. Farmers use pesticides to limit these effects.
- We formally analyse the interactions between crop biodiversity effects, trade and environmental policies that regulate the use of pesticides. Then, the implications on the volatility of food production and prices are derived.
- Contrary to the race-to-bottom tenet in environmental policies, at the symmetric equilibrium, restrictions on pesticides are more stringent under free trade than under autarky, even if their strigency diminishes when governments take into account their effect on the terms of trade.
- Because of the increase in the environmental tax, agricultural prices are generally higher and more volatile under trade, depending on the intensity of biodiversity effects.

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Abstract

Biotic factors such as pests create biodiversity effects that increase food production risks and decrease productivity when agriculture specializes. Under free trade, they reduce the specialization in food production that otherwise prevails in a Ricardian two-country setup. Pesticides allow farmers to reduce biodiversity effects, but they are damaging for the environment and for human health. When regulating farming practices under free trade, governments face a trade-off: they are tempted to restrict the use of pesticides compared to under autarky because domestic consumption partly relies on imports and thus depends less on them, but they also want to preserve the competitiveness of their agricultural sector on international markets. Contrary to the environmental race-to-the-bottom tenet, we show that at the symmetric equilibrium under free trade restrictions on pesticides are generally more stringent than under autarky. As a result, trade increases the price volatility of crops produced by both countries, and, depending on the intensity of the biodiversity effects, of some or all of the crops that are country-specific.

Keywords

Agricultural Trade, Food Prices, Agrobiodiversity, Pesticides.

JEL

F18, Q17, Q18, Q56.

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Food Trade, Biodiversity Effects and Price Volatility[1]

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1. Introduction

Agricultural prices are historically more volatile than manufacture prices (Jacks et al., 2011). Perhaps because this stochasticity is considered to be due to factors beyond human control, such as weather conditions, economic studies analyzing food price behavior focus mainly on factors related to market organization, such as demand variability and the role played by stocks.[2] However, in addition to abiotic factors, such as water stress, temperature, irradiance and nutrient supply, which are often related to weather conditions, production stochasticity is also caused by biotic factors, also known as "pests"—including animal pests (such as insects, rodents, birds, etc.), pathogens (such as viruses, bacteria, fungi, etc.), or weeds. These harmful organisms can cause critical harvest losses: the estimations of global potential yield losses for wheat, maize and rice, the three most produced cereals in the world, vary between 50% and 70% (Oerke, 2006).[3] The impact of pests on yields is linked to the degree of specialization of the agricultural sector, which depends on the country's openness to trade. The more cultivation is concentrated on a few high-yield crops, the more pests specialize on these crops and the greater their virulence. Yields become more variable and the probability of low harvests rises. Hence, while conventional wisdom is that trade decreases food price volatility, the specialization that it induces make

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[2]See Gilbert and Morgan (2010) and Wright (2011) for overviews on food price volatility and examinations of the causes of recent price spikes.
[3]Oerke (2006) defines "potential loss" as losses occuring when no pests control management procedures are used at all. Savary et al. (2000) and Fernandez-Cornejo et al. (1998) provide lower but nevertheless significant estimates of yield losses caused by pests.

the opposite effect more likely due to the impact of pests. This impact is very much reduced by the use of agrochemicals like pesticides, fungicides, herbicides and the like: for example, agrochemicals reduce potential losses of wheat by 50% (actual average losses are about 29%, with a minimum loss of 14% in Northwest Europe). Thanks to agrochemicals, losses due to pests have only a limited impact on the behavior of agricultural prices, the main factors being related to market organization. But chemicals generate negative externalities, on human health, biodiversity, water and air quality, which are a growing concern.[4] Trade questions the necessity of using pesticides, particularly for the local pollution they cause, because of NIMBY (Not in My Back Yard) considerations: food grown locally that is sold abroad exposes the local population to pesticide externalities without benefitting them personally. Besides, as a part of the food consumed locally is imported, pesticides that were used by domestic farmers to grow it under autarky are no longer needed under free trade. When opening to trade, the government regulating farming practices is faced with a trade-off: reducing the use of pesticides compared to under autarky allows to satisfy NIMBY concerns, but also reduces the trade competitiveness of the agricultural sector. The increasing awareness on agrochemicals externalities augments the weight of NIMBY considerations in public decisions and the use of pesticides seems to follow a decreasing trend (Ryberg and Gilliom, 2015; ECP, 2013; Bexfield, 2008).[5] A marked reduction in the use of pesticides would have clear environmental benefits but it could also raise food prices and their volatility, adding to the effects linked to food demand and stock management.

The aim of this paper is to analyze how crop biodiversity and environmental policies interact with trade. We develop a Ricardian trade model with decreasing returns driven by the negative effect of specialization on farm production, due to its impact on biotic factors, to represent the impact of crop biodiversity on agricultural productivity and on the pattern of trade. The formal description of the mechanisms at stake is also the first detailed examination of the potential role of biodiversity in the behavior of food prices. We single out these effects by assuming that the use of pesticides is regulated by an environmental tax with no distributional effects, and we abstract from risk aversion by assuming that

[4]Pimentel (2005) reports more than 26 million cases worldwide of non-fatal pesticides poisoning and approximately 220,000 fatalities. He estimates that the effects of pesticides on human health cost about $1.2 billion per year in the United States. Mammals and birds are also affected. Farmland bird population decreased by 25% in France between 1989 and 2009 (Jiguet et al., 2012), and a sharp decline was also observed in the whole EU during the same period (EEA, 2010). Pesticides also contaminate water and soils and significantly affect water species both locally and regionally (Beketov et al., 2013).

[5]Correlatively, demand for organic farming is rapidly increasing. In Europe, sales of organic products are estimated to be around €23 billion in 2012, a 6% increase from 2011's level (Schaack et al., 2014) and farmland devoted to them increased by more than 60% between 2005 and 2013. In the US, sales exceeded $34 billion in 2014 and have more than tripled between 2005 and 2014 (USDA-ERS, 2015). By replacing synthetic pesticides with natural ones and reducing their use, organic farming has a smaller environmental impact (Tuomisto et al., 2012) but also lower yields (Seufert et al., 2012) than conventional farming.

farmers and consumers are risk neutral.[6]

Our analysis provides three main findings. First, while countries have differing comparative advantage under autarky, biodiversity effects lead to incomplete specialization under free trade. Indeed, as specialization reduces the expected yield of crops, some of them are produced by both countries because their agricultural sectors end up with the same productivity at equilibrium. Second, the trade-off in the design of environmental policies results in restrictions on pesticides more stringent under free trade than under autarky: NIMBY considerations are prevalent over the market share rivalry that opposes the two countries. Third, the food price behavior depends on the pattern of trade. Trade increases the production volatility of crops produced by both countries. Country-specific crops for which comparative advantages are large could see a reduction in their volatility, but that supposes very small biodiversity effects. Concerning average prices, those of country-specific crops are increased for consumers of the producing country. This is because of more restrictive environmental policies and the intensification of production under free trade. For crops produced by both countries, the sharing of production determines the change in average prices.

Our work is related to different strains of literature. The link between crop biodiversity, yield and revenue variability is empirically investigated in Smale et al. (1998); Di Falco and Perrings (2005); Di Falco and Chavas (2006). These studies find sometimes contrasting results but generally tend to show that increasing agricultural biodiversity is associated with higher production and lower risk exposure (Di Falco, 2012). We add to this literature an economic foundation of the mechanisms at stake.[7] We build on Weitzman (2000) to model farm production with biodiversity effects: the larger the share of farmland dedicated to a crop, the more its parasitic species proliferates and thus the more fields of that crop are at risk of being wiped out.[8] Weitzman (2000) uses this model to solve the trade-off between the private and social optima, the former tending to specializing on a few varieties while the latter aims at preserving biodiversity. We depart from his work by considering a trade context, incorporating the use of pesticides, and investigating the impact of biodiversity effects on production and price distributions. Our setup is a Ricardian trade model with

[6] Risk aversion would lead the government to reduce specialization under trade to diversify production risks among countries, as demonstrated by Gaisford and Ivus (2014).

[7] For more details on the biological mechanisms involved, see Tilman et al. (2005), who use simple ecological models to describe the positive influence of diversity in the biomass produced and corroborate their findings with empirical results detailed in Tilman and Downing (1994) and Tilman et al. (1996).

[8] Weitzman (2000) makes an analogy between parasite-host relationships and the species-area curve that originally applies to islands: the bigger the size of an island, the more species will be located there. He compares the total biomass of a uniform crop to an island in a sea of other biomass. A large literature in ecology uses the species-area curve which is empirically robust not only for islands but, more generally, for uniform regions (May, 2000; Garcia Martin and Goldenfeld, 2006; Drakare et al., 2006; Plotkin et al., 2000; Storch et al., 2012).

two countries and many goods, à la Dornbusch et al. (1977). In this context, pests create external diseconomies of scale in the agricultural sector that generate increasing marginal costs in a perfect competition setup. A number of papers has studied external economies of scale in Ricardian models, from Ethier (1982) to Grossman and Rossi-Hansberg (2010) and Kucheryavyy et al. (2015). They focus on increasing returns to scale, which lead to what Grossman and Rossi-Hansberg (2010) call "pathologies", among which multiple equilibria and a reverse pattern of trade.[9] These outcomes do not arise in our context of decreasing returns to scale (only the lowest cost farmers produce), but these external scale effects cause incomplete specialization. In this Ricardian setup, we find an impact of trade on the strength of environmental policies. Previous literature has shown that international market share rivalry tends to weaken environmental policies (Barrett, 1994): by lowering environmental polices, the government reduces the marginal cost of domestic firms making them more competitive on international markets. However, governments may also be tempted to reduce polluting activities at home when the same products are produced abroad: Markusen et al. (1995) and Kennedy (1994) show that governments are induced to increase their environmental tax. Both effects are at work in our context, and we show that the latter is the main driving force in the setting of the environmental policy: taxes under free trade are larger than under autarky. Pests generating production risks, our study is also related to the literature on trade and uncertainty. The incorporation of risk in trade models dates back to Turnovsky (1974), who analyzes how the pattern of trade and the gains from trade are affected by uncertainty. Newbery and Stiglitz (1984) analyze how the production choices of risk-averse farmers are affected under free trade when production is uncertain and show that free trade may be Pareto inferior to no trade. Then, a whole range of literature looks at the optimal trade policy in presence of risk aversion, one of the recent contributions being Gaisford and Ivus (2014), who consider the link between protection and the size of the country. In these models, as well as in the recent Ricardian models involving more than two countries (Eaton and Kortum, 2002; Costinot and Donaldson, 2012), the stochastic component that affects production and determines the pattern of trade is not related to the production process itself. In that sense, it is "exogenous." We instead consider a stochastic component embedded in the production process and endogenously determined by the country's openness to trade: biotic and abiotic factors affect production stochastically, which generates price volatility, and also causes productivity losses that prevent complete specialization.

The rest of the paper is organized as follows: the next section details the relationship between crop biodiversity and the stochastic distribution of food productions. We determine the profit-maximizing equilibrium of the agricultural sector and show that biodiversity

[9]Indeed, with increasing returns to scale, production can be pushed towards the lowest cost producers as well as towards firms with higher costs but larger size, which allows them to remain competitive.

effects result in an incomplete specialization under free trade. Section 3 is devoted to the environmental policy. Optimal environmental tax policies are derived with and without biodiversity effects, and in two situations: when governments ignore the terms of trade effects of the tax and when they take them into account. This allows us to disentangle the consequences of the different concerns that define the tax policy under trade, i.e. the NIMBY considerations and the market share rivalry. The implication of the interaction between biodiversity effects and environmental policies on the volatility of food productions and prices is exposed in section 4. Comparative assessments are provided in section 5. Section H discuss briefly the impacts of trade on fertilizer use. The last section concludes.

2. The model

To investigate the importance of biodiversity effects on the pattern of trade and on the distributions of food prices, we re-examine the standard Ricardian model of trade as developed by Dornbusch et al. (1977). Here, we consider two-sector economies with an industrial/service sector which produces a homogeneous good (with equal productivities in the two countries and used as the numeraire) and an agricultural sector producing a range of goods with different potential yields. The effective yields depend on these potential yields but also on biotic and abiotic stochastic factors. They also depend on the use of pesticides, which is regulated by governments. The first part of this section details the farms' stochastic production setup and the resulting supply functions. Demands are derived in the second subsection. Then, we derive the autarky equilibrium. Although by assumption potential yields are different, consumer preferences and the other characteristics of the two economies lead to autarky situations that are symmetric in our framework: food average prices differ but the agricultural revenue, land rent and environmental tax are at the same levels in the two countries.

2.1. Production

Consider two countries (Home and Foreign) whose economies are composed of two sectors; industry and agriculture. Our focus being on agriculture, the industrial/service sector is summarized by a constant return to scale production technology that allows to produce one item with one unit of labor. The industrial good serves as the numeraire which implies that the wage in these economies is equal to 1. The agricultural sector produces a continuum of crops indexed by $z \in [0, 1]$ using three factors: land, labor and agrochemicals (pesticides, herbicides, fungicides and the like) directed to control pests and dubbed "pesticides" in the following.[10] Home and Foreign are endowed with L units of labor and N land plots

[10]In order to streamline the analysis, we don't consider fertilizers in the analysis. However, they can be easily incorporated in our model and the results are readily derived from the ones obtained on pesticides as

(Foreign values are denoted by L^* and N^* for clarity in the following, with asterisks used throughout the paper to refer to the foreign country). All land plots are of equal size, farmers are risk-neutral and may farm only one crop (the one they want) on one unit plot. As farming one plot requires one unit of labor, industry employs $L - N$ workers at equilibrium.

All plots are of equal productivity within a country, but technical coefficients differ from one crop to another and from one country to the other. More precisely, absent production externality and adverse meteorological or biological events, the mere combination of one unit of labor with one unit of land produces $\bar{a}(z)$ crop z in Home and $\bar{a}^*(z)$ in Foreign. Crops are ranked in order of diminishing Home's absolute yield: the relative crop yield $A(z) \equiv \bar{a}^*(z)/\bar{a}(z)$ satisfies $A'(z) > 0$, $A(0) < 1$ and $A(1) > 1$. Hence, on the basis of these differences in potential yield, Home is more efficient producing goods belonging to $[0, z_s)$ and Foreign over $(z_s, 1]$ where $z_s = A^{-1}(1)$.

However, crop production is affected by various factors resulting in an actual yield that is stochastic and lower than the potential one. Factors impacting production are both abiotic and biotic, the impact of the latter depending on the way crops are produced: the more land that is dedicated to the same crop, the more pests specialize on this crop, the higher the frequency of their attacks and the lower the survival probability of that crop (Pianka, 2011). To counteract the impact of external events on her plot, a farmer can avail herself of a large range of chemicals, but because of the externality due to pesticides (on human health and the environment) governments restrict their use. To ease the exposition and simplify the following derivations, we model the governmental policy as a tax which results in a pesticide's price τ, and we suppose that the governments complement this tax policy with a subsidy that corresponds to the average tax payment. Hence, while farmers choose individually and independently the amount of pesticides for their plot given the tax, at equilibrium, crop-taylored subsidies cover tax payments and pesticides levels correspond to the ones targeted by the government. The environmental policy is thus neutral for the public budget and for the farmers. More precisely, given her crop choice, farmer i chooses the intensity of the chemical treatment π_i on her field in order to reach expected income

$$r_i(z) \equiv \max_{\pi_i} \mathrm{E}[\tilde{p}(z)\tilde{y}_i(z)] - \tau\pi_i + T(z) - c,$$

where $\tilde{p}(z)$ is the stochastic crop z price, $\tilde{y}_i(z)$ her stochastic production level, $T(z)$ the subsidy for crop z, which is a lump sum payment to farmer i,[11] and c the other input costs,

explained in Appendix H.

[11] This lump sum transfer is given by $T(z) = \tau\pi(z)$ where $\pi(z)$ corresponds to the pesticides level used by a farmer of crops z at equilibrium. It is set prior to individual production decisions and thus does not depend on the quantity of pesticides used by farmer i, π_i.

i.e. the sum of the wage (one unit of labor is necessary to farm a plot of land) and the land rent, which is the same whatever crop is farmed. In the following, we assume that a unit plot is affected by one or several adverse conditions with probability $1-\psi$, independently of the fate of the other plots. If affected, its production is totally destroyed. Otherwise, with probability ψ, the plot survives and produces $\bar{a}(z)$.[12] This survival probability depends positively on the quantity π_i of pesticides used by farmer i, and on the average quantity of pesticides used by the other farmers of crop z in the country, $\bar{\pi}(z)$.[13] It also depends negatively on the share of land devoted nationally to the crop, $B(z) \equiv N(z)/N$ where $N(z)$ is the number of crop z plots. With atomistic individuals (N is so large that the yield of a single plot has a negligible effect on the market price), the crop z farmer's program can be rewritten as

$$r(z) = \max_{\pi_i} \bar{a}(z)\psi(\pi_i; z, \bar{\pi}(z), B(z))\bar{p}(z) - \tau\pi_i + T(z) - c,$$

where $\bar{p}(z)$ is the volume-weighted average price of crop z, defined as (denoting by $\tilde{y}(z)$ the total production level of crop z)

$$\bar{p}(z) \equiv \frac{\mathrm{E}[\tilde{p}(z)\tilde{y}(z)]}{\mathrm{E}[\tilde{y}(z)]} = p(z) + \frac{\mathrm{cov}(\tilde{p}(z), \tilde{y}(z))}{\mathrm{E}[\tilde{y}(z)]}. \tag{1}$$

As $\mathrm{cov}(\tilde{p}(z), \tilde{y}(z)) < 0$, this reference price $\bar{p}(z)$ is lower than the expected market price due to the correlation between total production $\tilde{y}(z)$ and market price $\tilde{p}(z)$. Solving the farmer's program, we obtain that the optimal level of pesticides at the symmetric Nash equilibrium between crop z farmers, $\pi(z)$, satisfies

$$\psi'(\pi(z); z, \pi(z), B(z)) = \frac{\tau}{\bar{a}(z)\bar{p}(z)}. \tag{2}$$

Assuming that the subsidy was set at $T(z) = \tau\pi(z)$ to allow farmers to break even at equilibrium,[14] and that competition in the economy leads to $r(z) = 0$ for all z, we get

$$\bar{a}(z)\psi(z)\bar{p}(z) = c, \tag{3}$$

where $\psi(z) \equiv \psi(\pi(z); z, \pi(z), B(z))$ is the survival probability of a plot of crop z at

[12]Pests and/or meteorological events do not necessarily totally destroy a plot, but rather affect the quantity of biomass produced. Our assumption allows for tractability, our random variable being the number of harvested plots rather than the share of harvested biomass.

[13]Indeed, pesticides have a positive impact on the treated plot as well as on the surrounding plots (even if these plots are not directly treated by their owners), since they diminish the overall level of pests. Hence, for a given individual treatment π_i, the larger $\bar{\pi}(z)$, the lower the probability that the plot of farmer i is infected.

[14]For the sake of simplicity, we consider neither the production nor the market of agrochemicals in the following. Implicitly, farmers are "endowed" with a large stock of agrochemicals that farming does not exhaust, leading to prices equal to 0.

equilibrium. As plots are identically and independently affected, we obtain that

$$\mathrm{E}[\tilde{p}(z)\tilde{y}(z)] = \bar{p}(z)\bar{a}(z)\psi(z)NB(z) = cNB(z), \tag{4}$$

i.e., the expected value of the crop z domestic production is equal to the sum of the wages and the land value involved in its farming.

The survival probability that allows us to derive our results in the following is given by[15]

$$\psi(\pi_i; z, \bar{\pi}, B) = \frac{\mu(z)e^{-(\theta(z)-\pi_i)^2/2}}{1+\kappa B e^{(\theta(z)-\bar{\pi})^2/2}}, \tag{5}$$

where $\mu(z) < 1$ is the maximum plot survival probability (which accounts for the impact of abiotic factors) and κ the cross-externality factor. The impact of farmer i's pesticides on the resilience of her plot appears on the numerator which reaches a maximum at $\pi_i = \theta(z)$, the unregulated level of pesticides. Biodiversity and cross-externality effects appear on the denominator: the expected resilience of farmer i's plot decreases with B, the intensity of the crop cultivation, but increases with the average level of pesticides $\bar{\pi}$ used on all other crop z plots.

Using (2), (3) and (5), we obtain that the pesticides level for crop z is given by

$$\pi(z) = \theta(z) - \tau/c, \tag{6}$$

and that the survival probability of a plot at equilibrium is given by

$$\psi(z) = \frac{\mu(z)}{t[1+t\kappa B(z)]}, \tag{7}$$

where $t \equiv e^{(\tau/c)^2/2}$ is the tax index that measures the negative effect of the restricted use of pesticides on the crop's resilience. This index reaches a minimum equal to 1 in the absence of regulation, i.e. $\tau = 0$. Denoting the crop z maximum expected yield as $a(z) \equiv \bar{a}(z)\mu(z)$, the crop z average price is given by

$$\bar{p}(z) = ct[1+t\kappa B(z)]/a(z), \tag{8}$$

and the expected domestic production level for crop z by

$$y(z) \equiv \mathrm{E}[\tilde{y}(z)] = \frac{a(z)NB(z)}{t[1+t\kappa B(z)]}. \tag{9}$$

[15]This functional form is a simplified version of a probabilistic model relying on a beta-binomial probability distribution and integrating externalities accross all crops. For more details, see Bellora et al. (2015).

Average production of crop z decreases with t because of two effects: the corresponding reduction in the use of pesticides has a direct negative impact on the productivity of each plot but also an indirect negative cross-externality effect between plots.

The other characteristics of the production distributions are derived from the assumptions that plots are independently affected by pests and that the survival probability (7) does not depend on the total number of plots N. As a result, the variance of crop z production is given by $\sigma(\tilde{y}(z))^2 = \bar{a}(z)^2 NB(z)\psi(z)[1-\psi(z)]$, and its distribution can be approximated by a Gaussian distribution $\mathcal{N}(y(z), \sigma(\tilde{y}(z)))$ when N is large.[16] Section 4 is devoted to the comparison of the volatility of food productions and prices under the different policy regimes we analyze in this paper.

2.2. Demand

The representative consumers of the two countries share the same preferences over goods, given by the following Cobb-Douglas utility function

$$U = b \ln x_I + (1-b)\int_0^1 \alpha(z) \ln \tilde{x}(z) dz - hZ,$$

where $\int_0^1 \alpha(z)dz = 1$ and $h > 0$. The first two terms correspond to the utility derived from the consumption of industrial and agricultural goods respectively, while the last term corresponds to the disutility of the environmental damages caused by a domestic use of

$$Z = N\int_0^1 B(z)\pi(z)dz$$

pesticides by farmers. The demand for the industrial good is $x_I = bR$ where R is the revenue per capita. The rest of the revenue, $(1-b)R$, is spent on food with individual demand for crop z given by

$$\tilde{x}(z) = \alpha(z)(1-b)R/\tilde{p}(z) \tag{10}$$

where $\tilde{p}(z)$ depends on the realized production level $\tilde{y}(z)$ and $\alpha(z)$ is the share of the food spending devoted to crop z. We assume that consumers are risk-neutral and thus evaluate their *ex ante* welfare at the average consumption level of crop z, $x(z) \equiv \mathrm{E}[\tilde{x}(z)]$. At market equilibrium under autarky (the same reasoning applies under free trade), as $L\tilde{x} = \tilde{y}$, we obtain from (1) and (10) that the volume-weighted average price $\bar{p}(z)$ is equal

[16] Denoting by $\tilde{X}(z)$ the number of plots that survive to pests, this random variable follows a binomial distribution of parameters $NB(z)$, the number of plots growing crop z, and $\psi(z)$, the survival probability of each of these plots: we have $\tilde{y}(z) = \bar{a}(z)\tilde{X}(z)$ and thus $\mathrm{Var}(\tilde{y}(z)) = \bar{a}(z)^2\mathrm{Var}(\tilde{X}(z))$, with $\mathrm{Var}(\tilde{X}(z)) = NB(z)\psi(z)[1-\psi(z)]$. Because $\psi(z)$ does not depend on N, the central limit theorem applies and the distribution of $\tilde{X}(z)$ converges to a normal distribution when N is large.

to $\mathrm{E}[1/\tilde{p}(z)]^{-1}$. The representative consumer's indirect utility function can be written as[17]

$$V(R, Z) = \ln(R) - (1-b)\int_0^1 \alpha(z)\ln\bar{p}(z)dz - hZ. \tag{11}$$

where $R = (L - N + cN)/L$: since there is no profit or tax proceeds at equilibrium, the national revenue is the sum of the land rent and the wages.

The government determines the optimal policy by maximizing this utility, taking account of the relationship between pesticides and the land rent.

2.3. Equilibrium under autarky

The autarky equilibrium is derived as follows. The market clearing condition for industrial goods allows us to derive the cost of food production c_A (the sum of the land rent and the wage).[18] For a given level of the environmental tax, equilibrium on each crop market gives the sharing of land between crops. These levels allow us to derive the optimal tax policy under autarky.

Due to the constant returns to scale in the industrial sector, the total spending on industrial products must be equal to the total production cost at equilibrium, i.e.,

$$bLR = L - N$$

where the total domestic revenue is given by

$$LR = Nc_A + L - N. \tag{12}$$

Denoting $\ell \equiv L/N > 1$, we obtain $c_A = (\ell - 1)(1-b)/b$ and the land rent is positive if $\ell > 1/(1-b)$, i.e. if the population is sufficiently large, a condition assumed to hold in the following. Due to the Cobb-Douglas preferences and the constant productivity in the industrial sector, this value depends neither on the use of pesticides nor on the crops' prices and is the same in both countries in spite of their crop yield differences.

Equilibrium on the crop z market implies that total expenses are equal to total production cost, i.e.

$$\alpha(z)(1-b)LR = NB(z)c_A.$$

Using (12) and $c_A = (\ell-1)(1-b)/b$, we obtain that the share of land devoted to crop z satisfies $B(z) = \alpha(z)$. Using (6) and $\tau/c = \sqrt{2\ln t}$, the total quantity of pesticides used

[17] Up to a constant given by $b\ln(b) + (1-b)\int_0^1 \alpha(z)\ln\alpha(z)dz$.

[18] Subscript "A" indexes equilibrium values under autarky.

is given by

$$Z = N\int_0^1 \alpha(z)\theta(z)dz - N\sqrt{2\ln t}.$$

The optimal tax index is determined by maximizing the utility of the representative consumer (11) which reduces to

$$\min_t (1-b)\int_0^1 \alpha(z)\ln\{t[1+t\kappa\alpha(z)]\}dz + hZ,$$

a program that applies to both countries. We obtain that the optimal tax index under autarky, t_A, solves

$$\sqrt{2\ln t_A}\left[1+\int_0^1 \frac{t_A\kappa\alpha(z)^2}{1+t_A\kappa\alpha(z)}dz\right] = \frac{Nh}{1-b}. \quad (13)$$

The optimal tax is maximum for $\kappa = 0$, given by $\tau_A = (L-N)h/b$, and decreases when κ increases: the government should allow farmers to use more pesticides when biodiversity effects are large.

While acreage and pesticides levels are the same in both countries under autarky, their average productions are different because of the differences in crop yields. The revenue being the same in both countries, crop demands are identical but because average production levels are different, break-even prices are also different.

2.4. Free trade equilibrium

We show in this section that when Home and Foreign engage in free trade, biodiversity effects result in an incomplete specialization. Without these effects, productions are country-specific as described in Dornbusch et al. (1977), a threshold crop delimiting the production range specific to each country. With biodiversity effects, this clear-cut situation can no longer exist, because specialization, i.e. the increase in the acreage devoted to a crop, reduces the expected yield. As a result, the two countries share the production of a whole range of crops delimited by two threshold crops.[19] We detail these results in the next paragraphs.

The free trade equilibrium is derived from the equilibrium on industrial good market which allows us to determine the worldwide agricultural and total revenues. The condition of equalization of total spending with the total production cost on the industrial market is given by

$$b(Nc + L - N + N^*c^* + L^* - N^*) = L - N + L^* - N^*$$

[19] Incomplete specialization is obtained in Dornbusch et al. (1977) considering exogenous trade costs, the so-called Samuelson's iceberg costs. In our setup, it is due to stochastic factors that are directly linked to the production process and evolve with the openness to trade.

where $L = L^*$ and $N = N^*$. We obtain $c + c^* = 2(\ell - 1)(1 - b)/b$, hence that the worldwide agricultural revenue (i.e., land rent) is the same as under autarky. This is also the case for the total revenue, given by

$$LR + L^*R^* = N[c + c^* + 2(\ell - 1)] = 2N(\ell - 1)/b.$$

As under autarky, the share of the agricultural sector of this revenue is unchanged, given by $1 - b$. For Home, it results in a per-individual revenue given by

$$R = \frac{(\ell - 1)}{\ell}\left[1 + 2q\frac{1 - b}{b}\right], \tag{14}$$

which depends on the domestic share of the worldwide agricultural market $q \equiv c/(c + c^*)$ obtained at equilibrium. This share depends on crop yields, that determine the comparative advantages of each country, and thus on the environmental tax policies implemented in each country.

However, competitive advantages depend not only on environmental taxes but also on biodiversity effects, i.e. on the way land is farmed. Indeed, for a given tax level, the higher the intensity of the farming of a crop, i.e. the more land is devoted to that crop, the lower the average productivity of the land, because of the production externality effect. In other words, intensification undermines the competitive advantages apparent under autarky. More precisely, if crop z is produced by Home only, the market equilibrium condition implies that worldwide expenses on crop z are equal to total production cost, i.e.,

$$2\alpha(z)(\ell - 1)N(1 - b)/b = NB(z)c$$

which can be written as $\alpha(z)/q = B(z)$. Opening to trade could thus correspond to a large increase of the acreage devoted to that crop: for example, if $q = 1/2$, its total farmland doubles which may seriously impair Home's land productivity for crop z. Hence, because of the production externality, it is possible that a whole range of crops is only partially traded. A crop is produced by both countries under two conditions: the equality of the two countries break-even prices and an equilibrium market value worldwide equal to the sum of the two countries production costs. The first condition leads to the following equation, using (8):

$$A(z) = \frac{c^*}{c}\frac{t^*}{t}\frac{1 + t^*\kappa B^*(z)}{1 + t\kappa B(z)}. \tag{15}$$

The second condition leads to

$$2\alpha(z)N(\ell - 1)(1 - b)/b = cNB(z) + c^*N^*B^*(z),$$

which can also be written as

$$\alpha(z) = qB(z) + q^*B^*(z). \tag{16}$$

Crop z is produced by both countries if there exist $B(z) > 0$ and $B^*(z) > 0$ that solve (15) and (16). As stated formally in the following proposition, this is true for a whole range of crops. More precisely,

Proposition 1 *Specialization is incomplete under free trade: Assuming κ is not too large, both countries produce crops belonging to $(\underline{z}, \bar{z})$, $0 \leq \underline{z} < \bar{z} \leq 1$ satisfying*

$$A(\bar{z}) = \frac{t^*}{t}\frac{q^* + t^*\kappa\alpha(\bar{z})}{q} \tag{17}$$

and

$$A(\underline{z}) = \frac{t^*}{t}\frac{q^*}{q + t\kappa\alpha(\underline{z})}. \tag{18}$$

The intensity of these crops is given by

$$B(z) = \chi(z)\frac{1 - q\phi(z)}{q} \tag{19}$$

where

$$\phi(z) \equiv \frac{1 + A(z)t/t^*}{1 + \alpha(z)t^*\kappa}, \tag{20}$$

$$\chi(z) \equiv \frac{1 + t^*\alpha(z)\kappa}{t\kappa[A(z)t/t^* + t^*/t]} \tag{21}$$

for Home and symmetric expressions hold for Foreign (with $A(z)$ replaced by $1/A(z)$). Crops belonging to $[0, \underline{z}]$ are produced by Home only, with intensity $B(z) = \alpha(z)/q$, and crops belonging to $[\bar{z}, 1]$ are produced by Foreign only, with intensity $B^*(z) = \alpha(z)/q^*$.

Proof: see the appendix.

Without any biodiversity effect, i.e. with $\kappa = 0$, using (17) and (18), we end up with $A(\bar{z}) = A(\underline{z}) = (q^*/q)(t^*/t)$ and thus a unique threshold index and complete specialization. With biodiversity effects, i.e. with $\kappa > 0$, we have $A(\underline{z}) < A(\bar{z})$ and since A is strictly increasing, $\underline{z} < \bar{z}$. For crops ranging between $\underline{z}$ and $\bar{z}$, albeit technical differences exist between the two countries, comparative advantages are trimmed by the negative externality that affects national production of each country.

Expected production levels and break-even prices are easily derived from these results. We obtain:

Lemma 1 *Under free trade, Home and worldwide expected productions of crops produced by both countries, i.e. crops $z \in (\underline{z}, \bar{z})$, are given by*

$$y_T(z) = Na(z)\frac{q^* + \alpha(z)\kappa t^* - qA(z)t/t^*}{t\kappa[qt^* + q^*t + tt^*\alpha(z)\kappa]}$$

and

$$y_T^W = N\frac{\alpha(z)[a^*(z)t_T/t_T^* + a(z)t_T^*/t_T]}{qt_T^* + q^*t_T + \alpha(z)t_T t_T^*\kappa}$$

respectively. For these crops the break-even price is

$$\bar{p}_m(z) = \frac{2(1-b)(\ell-1)}{ba(z)}\frac{q(t^*-t) + t[1+\alpha(z)t^*\kappa]}{t^*/t + A(z)t/t^*}. \tag{22}$$

For the other crops, the corresponding expected productions and break-even prices are given by

$$y(z) = \frac{a(z)N\alpha(z)}{t[q + t\kappa\alpha(z)]}$$

and

$$\bar{p}_s(z) = \frac{2(\ell-1)(1-b)t[q + t\kappa\alpha(z)]}{ba(z)} \tag{23}$$

for all $z \leq \underline{z}$ and by symmetric expressions for all crops $z \geq \bar{z}$. The level of pesticides used by Home under free trade is given by

$$Z_T = \frac{N}{q}\left\{\int_0^{\underline{z}} \alpha(z)\theta(z)dz + \int_{\underline{z}}^{\bar{z}} \chi(z)[1 - q\phi(z)]\theta(z)dz\right\} - N\sqrt{2\ln t}. \tag{24}$$

Proof: direct from the preceding results.

These expressions depend on the environmental taxes and how the worldwide agricultural revenue is shared. To determine this share, we can use the fact that the domestic revenue comes from the sale of the goods produced nationally.[20] On interval $[0, \underline{z}]$, all revenues spent are collected by Home, while it is only a share $s(z) \equiv y_T(z)/y_T^W(z)$ of them on $[\underline{z}, \bar{z}]$. We thus have

$$q = \int_0^{\underline{z}} \alpha(z)dz + \int_{\underline{z}}^{\bar{z}} s(z)\alpha(z)dz \tag{25}$$

where, using (4) and (16),

$$s(z) = \frac{y_T(z)}{y_T(z) + y_T^*(z)} = \frac{qB(z)}{qB(z) + q^*B^*(z)} = \frac{qB(z)}{\alpha(z)} \tag{26}$$

[20]The same expression can be derived using the equilibrium condition on the land market.

Replacing in (25) and using (19), we get

$$q = \frac{\int_0^{\underline{z}} \alpha(z)dz + \int_{\underline{z}}^{\overline{z}} \chi(z)dz}{1 + \int_{\underline{z}}^{\overline{z}} \phi(z)\chi(z)dz} \tag{27}$$

which also depends on the taxes t and t^* that are implemented at equilibrium. Hence, environmental tax policies determine the sharing of worldwide agricultural revenue and therefore drive the free trade equilibrium. The next section details the way they are determined.

3. Environmental tax policy and trade

To formalize the competition between the two countries, we assume that the taxes on pesticides result from the Nash equilibrium of a two-stage game. In the first stage, Home and Foreign governments choose simultaneously their tax policies. In the second stage farmers decide which crops to sow and how much pesticides to use. Home's government problem when defining its tax policy corresponds to the following program:

$$\max_t \ln(R) - (1-b)\left\{\int_0^{\underline{z}} \alpha(z)\ln \bar{p}_s(z)dz + \int_{\underline{z}}^{\overline{z}} \alpha(z)\ln \bar{p}_m(z)dz + \int_{\overline{z}}^1 \alpha(z)\ln \bar{p}_s^*(z)dz\right\} - hZ \tag{28}$$

where $\bar{p}_s^*(z)$ is given by (23) with t and q replaced by t^* and $q^* = 1 - q$. The optimal environmental policy resulting from this program depends on t^*: maximizing (28) gives Home's best-response to Foreign's policy t^*. Foreign's government is in the symmetric situation, since both governments act simultaneously in a strategic way.

For the sake of argument, we consider two cases in the following. In the first case, governments ignore the relationship between their tax policies and their share of the worldwide agricultural revenue; we call the resulting free trade equilibrium "non-strategic". In the second case, which is more realistic and that we call "strategic trade", governments reckon that the land rent, and thus the total revenue R, depends on environmental taxes, t and t^*.[21] Indeed, one may easily show that Home's share of world agricultural revenue, q, is related negatively to its environmental tax t and positively to t^*. A total differentiation of (25) yields, using $s(\overline{z}) = 0$ and $s(\underline{z}) = 1$,

$$\frac{dq}{dt} = \frac{\int_{\underline{z}}^{\overline{z}} [B(z)(d\chi(z)/dt)/\chi(z) - \chi(z)(d\phi(z)/dt)]dz}{1 + \int_{\underline{z}}^{\overline{z}} \phi(z)\chi(z)dz} \tag{29}$$

[21] It is thus a "strategic environmental policy game" as analyzed by Barrett (1994) in an oligopoly setup à la Brander and Spencer (1985) where governments want to increase the profit of their firms through a larger world market share.

where it is straightforward from (21) and (20) that $d\chi(z)/dt < 0$ and $d\phi(z)/dt > 0$. Hence, we have $dq/dt < 0$ and since $q + q^* = 1 - b$, $dq^*/dt = -dq/dt > 0$. Because of the strategic substituability of the environmental taxes, pesticides are used more intensively at the strategic trade equilibrium than when governments act non strategically.

To detail this competition effect and assess its interaction with the biodiversity externality that affects production, we consider in the following the case where $\alpha(z) = 1$ and $\theta(z) = \theta$ for all z. Hence, neither the demand nor the externality on consumers' utility distinguishes crops, and the total use of pesticides simplifies to $Z = N\theta - N\sqrt{2\ln t}$. We also suppose that $A(z)$ allows us to obtain symmetric equilibria so that $q = 1/2 = z_s$ at equilibrium. We analyze the two types of free trade equilibria (non-strategic and strategic) assuming first that there is no biodiversity effect, i.e. $\kappa = 0$. In this case, while there are no cross-externality effects between fields of the same crop, farmers still have an incentive to spread pesticides on their plots to increase their expected yield. We then introduce the negative production externality ($\kappa > 0$), which induces decreasing returns to scale in the agricultural sector at the national level.

3.1. Trade without biodiversity effect

As noted above, without biodiversity effect, i.e. when $\kappa = 0$, the environmental tax under autarky is given by $\tau_A = (L - N)h/b$. Under free trade, each country specializes on one segment of the range of crops delimited by threshold z_s which satisfies $A(z_s) = (q^* t^*)/(qt)$ using (15). Equilibrium on the land market, $\int_0^{z_s} B(z)dz = \int_0^{z_s}(1/q)dz = 1$, leads to $q = z_s$: Home's share of the worldwide agricultural revenue is equal to the range of crops produced domestically. Consequently z_s solves $\xi(z_s) = t^*/t$ where $\xi(z) \equiv A(z)z/(1-z)$ is strictly increasing.

In the non-strategic situation, governments do not take into account the effect of their environmental taxes on the sharing of the agricultural revenue. The effect of the tax policies on z_s, q and R are neglected when solving (28). The problem simplifies to

$$\min_t (1-b)q\ln t - hN\sqrt{2\ln t}$$

where q is considered as a constant. The first-order condition leads to an optimal tax index that solves

$$\sqrt{2\ln t} = \frac{Nh}{q(1-b)}. \tag{30}$$

Using $q = z_s$, we obtain that the threshold crop solves

$$\xi(z_s) = \exp\left\{\frac{(Nh)^2(1-2z_s)}{2[(1-b)z_s(1-z_s)]^2}\right\}.$$

As $\sqrt{2\ln t} = \tau/c$ and $c = 2qc_A$, (30) allows us to obtain $\tau = 2\tau_A$ whatever the country's share of the worldwide agricultural revenue.[22] Stated formally:

Proposition 2 *Suppose that there are no biodiversity effects. Then, at the non-strategic trade equilibrium, the environmental tax is doubled compared to under autarky.*

The intuition is as follows. The environmental policy affects only crops produced domestically. As their range is smaller under free trade than under autarky, the impact of the environmental policy on consumer welfare is reduced on the consumption side (prices affected by the tax are only those produced by Home) while it is unchanged on the environmental side. It is thus optimal to raise the tax compared to under autarky. Trade creates a NIMBY effect: while consumers benefit from the low prices allowed by pesticides used abroad, they want the use of pesticides restricted domestically to reduce pollution.[23] Observe that the resulting situation is not Pareto optimal: indeed, if the two countries could agree on tax levels, each would have to account for the price effect of its tax on the other country's consumers. In our setup, the resulting Pareto optimal tax level is the autarky one.[24]

Now suppose that governments are strategic in the sense that they take into account the effect of the tax on their shares of agricultural revenue. Using (14) and (28) we obtain that Home's best-response to t^* solves

$$\max_{t,q}\left\{\ln\left(1+\frac{2q(1-b)}{b}\right)-(1-b)\left[\int_0^q \ln \bar{p}_s(z)dz+\int_q^1 \ln \bar{p}_s^*(z)dz\right]-hZ : q=\xi^{-1}\left(\frac{t^*}{t}\right)\right\}.$$

It is implicitly defined by

$$\sqrt{2\ln t}\left\{q+\left[\frac{2}{b+2q(1-b)}\right]\frac{t^*}{t\xi'(z_s)}\right\}=\frac{Nh}{1-b}. \tag{31}$$

At a symmetric equilibrium, i.e. $q = 1/2 = z_s$, $t = t^*$, which implies that $A(1/2) = 1$ and thus $\xi'(z_s) = A'(1/2) + 4$, we get

$$\sqrt{2\ln t}=\frac{Nh}{1-b}\left[1+\frac{A'(1/2)}{A'(1/2)+8}\right].$$

The following proposition characterizes the optimal policy at equilibrium:

[22]The fact that the taxes are the same at equilibrium is due to the specifics of our model and the assumption that $\alpha(z) = 1$ and $\theta(z) = \theta$ for all z, whereas the revenues in the two countries are generally different.
[23]Markusen et al. (1995) and Kennedy (1994) obtain comparable results in an imperfect competition framework. When domestic consumers have access to the goods produced in the foreign country, governments are induced to increase their environmental tax.
[24]Indeed, for any sharing $(q, 1-q)$ of the agricultural revenue $2c_A$, the Pareto optimal tax levels solve $\min_t 2(1-b)q\ln t - hN(2\ln t)^{1/2}$ and the equivalent program for Foreign.

Proposition 3 *Suppose that there are no biodiversity effects. Then, at the symmetric strategic trade equilibrium, the environmental tax τ verifies $2\tau_A > \tau \geq \tau_A$, with $\tau = \tau_A$ in the limit case where $A'(1/2) = 0$. Moreover, the steeper the comparative advantage function $A(z)$, the larger the environmental tax.*

Proof: see the appendix.

When comparative advantages are not too different, allowing farmers to use more pesticides could have a large impact on the country's market share of agricultural products. Both governments have the same incentives to lower taxes and at the symmetric equilibrium, countries do not gain market share. However, as this rivalry counteracts the NIMBY effect described above, this ineffective competition in terms of market share results in a situation which is a Pareto improvement compared to the non-strategic one.

3.2. Biodiversity effects

Biodiversity effects create two countervailing distortions in the governments' trade-off we have described above. On the one hand, as specialization induced by trade increases the production externality that impedes production, governments should be induced to lower the tax on pesticides with respect to under autarky. On the other hand, as the externality limits specialization, the effect of the tax on prices concerns a reduced set of crops, which should induce governments to increase the tax.

To give a comprehensive appraisal of these countervailing effects, we consider a particular form of the relative potential yield function, given by

$$A(z) = \frac{1 + m(2z-1)}{1 - m(2z-1)} \tag{32}$$

where $0 < m < 1$. The larger m, the larger the discrepancy between the countries' relative potential yield away from $z = 1/2$ (graphically, the relative potential yield curve becomes steeper when m increases). With this particular form, at a symmetric equilibrium, threshold crops given by (17) and (18) simplify to

$$\bar{z} = \frac{1}{2} + \frac{t\kappa}{2m(1+t\kappa)} \tag{33}$$

and

$$\underline{z} = \frac{1}{2} - \frac{t\kappa}{2m(1+t\kappa)}. \tag{34}$$

They are equally distant from the centre of the range of crops (1/2), and the length of the subset of crops produced by both countries,

$$\bar{z} - \underline{z} = \frac{1}{m}\frac{t\kappa}{1 + t\kappa}, \tag{35}$$

increases with κ and t and decreases with the relative potential yield parameter m.

In the non-strategic case, the condition that determines t at the symmetric equilibrium can be written as $(\partial V/\partial t)_{t^*=t} = 0$ where

$$\left.\frac{\partial V}{\partial t}\right|_{t^*=t} = -\frac{1-b}{t}\left[\frac{1+4t\kappa}{1+2t\kappa}\underline{z} + (\bar{z} - \underline{z})\frac{1+2t\kappa}{2(1+t\kappa)}\right] - h\frac{dZ}{dt}. \tag{36}$$

The last term corresponds to the environmental impact of the tax on consumers, which is positive since $dZ/dt < 0$. It leads the government to increase the environmental tax. The bracketed term is composed of two elements, the first one corresponding to the price effect on the goods produced locally and the second one to the price effect on the goods produced by both countries. In these terms, biodiversity effects are ambiguous. Indeed, using (34) and (35), the effect on goods produced locally can be rewritten as

$$\frac{1+4t\kappa}{1+2t\kappa}\underline{z} = \left(1 + \frac{2t\kappa}{1+2t\kappa}\right)\left(\frac{1}{2} - \frac{\bar{z} - \underline{z}}{2}\right).$$

In the first bracket, the fraction $2t\kappa/(1+2t\kappa)$ tends to reduce the tax on crops produced locally, compared to the case where $\kappa = 0$. The second bracketed term highlights that the range of crops specific to Home is not half of the total but is reduced by $(\bar{z} - \underline{z})/2$, which tends to increase the tax. The increase in the range of crops produced by both countries has a second effect, contrary to the one just described, as shown by the term $(\bar{z} - \underline{z})(1+2t\kappa)/[2(1+t\kappa)]$ in (36). However, the effect due to the decrease in the range of specific crops exceeds the one concerning crops produced by both countries. Indeed, we have

$$\frac{\bar{z} - \underline{z}}{2}\left(1 + \frac{2t\kappa}{1+2t\kappa} - \frac{1+2t\kappa}{1+t\kappa}\right) = \frac{\bar{z} - \underline{z}}{2}\left(\frac{2t\kappa}{1+2t\kappa} - \frac{t\kappa}{1+t\kappa}\right) > 0.$$

Hence, in the end, the fact that both countries are producing crops belonging to $(\underline{z}, \bar{z})$ tends to increase the tax level compared to the case where $\kappa = 0$. As a result, the environmental tax could be larger or lower than $2\tau_A$, depending on the relative potential yields of crops. More precisely, we have the following result:

Proposition 4 *Suppose that the relative potential yield function is given by (32). Then, at the symmetric non-strategic trade equilibrium, biodiversity effects result in a reduction of the environmental tax compared to the case where $\kappa = 0$ unless m is very small. Overall, the environmental tax is greater than under autarky.*

Proof: see the appendix.

When the discrepancy in relative potential yields is large between the two countries, specialization is important (the range of crops produced by both is relatively small), and the cross externality effect is optimally contained by an intensive use of pesticides.

In the strategic case, there is a marginal effect of the environmental tax on the share of the agricultural revenue that induces governments to reduce their environmental tax. Indeed, the marginal effect of the tax policy on welfare entails an additional term compared to the non-strategic case. It is given by

$$\frac{dV}{dt} = \frac{\partial V}{\partial t} + \frac{\partial V}{\partial q}\frac{dq}{dt}$$

where

$$\frac{\partial V}{\partial q} = \frac{2(1-b)}{b+2q(1-b)} - (1-b)\left[\frac{\underline{z}}{q+t\kappa} - \frac{1-\bar{z}}{1-q+t^*\kappa} + \frac{(\bar{z}-\underline{z})(t^*-t)}{q(t^*-t)+t(1+t^*\kappa)}\right]. \quad (37)$$

The first term corresponds to the direct effect on welfare due to the increase in revenue while the remaining terms concern the effects on the price of crops produced domestically, abroad and by both countries respectively. At a symmetric equilibrium, the price effects cancel out, leading to $(\partial V/\partial q)_{t^*=t,q=1/2} = 2(1-b)$. Using (32) and (29), we obtain that

$$\left.\frac{dq}{dt}\right|_{t^*=t,q=1/2} = -\frac{3+9t\kappa+4(t\kappa)^2}{12t(1+t\kappa)[m(1+t\kappa)+1]} \quad (38)$$

which decreases with κ. The greater the biodiversity effects, the stronger the negative impact of the environmental tax on the share of the agricultural revenue. However, notwithstanding the marginal effect of the tax on the revenue, we show in the appendix the following result

Proposition 5 *Suppose that the relative potential yield function is given by (32). Then, at the symmetric strategic trade equilibrium the environmental tax is generally greater than under autarky.*

Proof: see the appendix.

We conclude this section by summarizing the main effects of trade on the pesticides policy. When governments neglect the impact of the tax on the revenues of the domestic farmers (i.e. under non strategic trade) and without biodiversity effects, the NIMBY effects described in section 3.1 drive the increase in taxes. Still under non strategic trade but with biodiversity effects, the production externality leads to a decrease in the taxes, counteracting the NIMBY effect. However, the tax remains higher than under autarky. In the strategic case, the marginal effect of the environmental tax on the market share leads governments to soften their environmental policy. Nevertheless, the environmental policy remains more stringent under free trade than under autarky.

4. Trade and volatility

Food production is affected both by the way land is farmed, which depends on the specialization induced by trade, and by the public regulation on pesticides. This section is devoted to the impacts of these elements on the fluctuations in food productions and prices.

4.1. Production volatility

To compare the distributions between the autarky and the free trade situations, we use as a volatility measure the variation coefficient (VC) which is defined for the random variable $\tilde{X}$ as the ratio of its standard deviation to its expectation: $v(\tilde{X}) \equiv \sigma(\tilde{X})/\mathrm{E}(\tilde{X})$. The amplitude of fluctuations is thus expressed as a percentage of the mean value. As plots are independently affected by pests, the variance of crop z domestic production is given by $\mathrm{Var}(\tilde{y}(z)) = \bar{a}(z)^2 NB(z)\psi(z)[1-\psi(z)]$. Using (7) and (9), the variation coefficient for the production by Home of a crop z is given by

$$v(\tilde{y}(z)) = \left\{ \frac{t[1+t\kappa B(z)] - \mu(z)}{\mu(z)NB(z)} \right\}^{1/2}. \tag{39}$$

This coefficient increases with the tax index t and the intensity of biodiversity effects κ, while it decreases with the total number of plots N and the share of the agricultural area dedicated to the considered crop, B. Indeed, due to independence, both the variance and the mean of the production increase linearly with N. As the VC is proportional to the standard deviation, we obtain a negative "scale" effect on volatility: without changing the proportion of farmland devoted to each crop, the larger the agricultural area of the country, the lower the standard deviation of each production compared to the mean. There is also a scale effect associated to intensification (an increase in B) that dominates biodiversity effects: increasing the share of farmland devoted to a crop increases both the expected value and the spread of the harvest, but the former raise is larger. The variation coefficients of the worldwide production of crop z under autarky are given by

$$v(\tilde{y}_A^W(z)) = \frac{[\mathrm{Var}(\tilde{y}_A(z)) + \mathrm{Var}(\tilde{y}_A^*(z))]^{1/2}}{\tilde{y}_A(z) + \tilde{y}_A^*(z)} = \frac{\{[\bar{a}(z)^2 + \bar{a}^*(z)^2]N\alpha(z)\psi(z)[1-\psi(z)]\}^{1/2}}{[\bar{a}(z) + \bar{a}^*(z)]N\alpha(z)\psi(z)}.$$

Using (7), we get

$$v(\tilde{y}_A^W(z)) = \left\{1 - \frac{2A(z)}{[1+A(z)]^2}\right\}^{1/2} \left\{\frac{t_A[1+t_A\kappa\alpha(z)] - \mu(z)}{\mu(z)N\alpha(z)}\right\}^{1/2}. \quad (40)$$

While the second bracketed term in (40) is similar to (39), the first term reveals a yield effect on production volatility: as $A(z)/[1+A(z)]^2$ is cap-shaped with a maximum at $A(z) = 1$, this effect is decreasing for $z < 1/2$ and increasing for $z > 1/2$. Hence, the yield effect on volatility is higher the larger the difference between the crop yields of the two countries.[25]

Assuming symmetry, $\alpha(z) = 1$ and $\mu(z) = \mu$ for all z, the volatility of domestic production is the same for all crops under autarky and, at a different level, for all country specific crops under free trade. Indeed, in these two cases, the intensification effects are constant, since, under autarky, $B(z) = 1$ for all z and, under free trade, $B(z) = 2$ for all crops in the range $[0; \underline{z}[$ and $B^*(z) = 2$ for all crops in the range $]\bar{z}; 1]$. However, the effects of intensification under free trade vary from one crop to the other when we consider crops produced by both countries ($z \in [\underline{z}; \bar{z}]$) since farmland intensities vary. The total share of land devoted to crops at the symmetric equilibrium is the same ($B(z) + B^*(z) = 2$ in any case), but the relative importance of Home is decreasing with z (from $B(\underline{z}) = 2$ to $B(\bar{z}) = 0$), whereas it is constant under autarky. To compute the volatility of the world production of crops produced by both countries we use $\text{Var}(\tilde{y}^W(z)) = \text{Var}(\tilde{y}_T(z)) + \text{Var}(\tilde{y}_T^*(z))$ and $v(\tilde{y}^W(z))^2 = s(z)^2 v(\tilde{y}(z))^2 + s^*(z)^2 v(\tilde{y}^*(z))^2$, which lead to

$$v(\tilde{y}^W(z)) = \left\{\frac{(1+t\kappa)(1+2t\kappa) - \mu\kappa}{2\mu N\kappa} - \frac{2(1+t\kappa)^2}{\mu N\kappa}\frac{A(z)}{[1+A(z)]^2}\right\}^{1/2}. \quad (41)$$

As with (40), there is a yield effect at work: the volatility index is decreasing over $[\underline{z}, 1/2)$, increasing over $(1/2, \bar{z}]$, and thus reaches a minimum at $z = 1/2$. Comparing the VCs under autarky and trade, we obtain the following result:

Proposition 6 *Without biodiversity effects, trade could potentially reduce the production volatility of all crops. However, because of a higher environmental tax than under autarky, only the volatility of crops for which countries have large comparative advantages is reduced (if any). With biodiversity effects, trade increases the production volatility of crops produced by both countries and of the specialized crops with moderate competitive advantage. The volatility of large comparative advantage crops is reduced only if biodiversity effects are small and the environmental tax not too different from its autarky level.*

Proof: see the appendix.

[25] With identical yields, i.e. $A(z) = 1$, this term is equal to $\sqrt{2}/2$, the scale effect of a doubling of farmland.

4.2. Price volatility

Some characteristics of the food price distributions can be derived from the properties of the production distributions that are approximatively Gaussian when N is large. First, observe that the volume-weighted average price $\bar{p}(z)$ corresponds to crop z median price: we have $\Pr[\tilde{p}(z) \leq \bar{p}(z)] = \Pr[\tilde{y}(z) \geq y(z)] = 1/2$ since the normal distribution is symmetric. Consequently, as $\bar{p}(z)$ is lower than the average market price $p(z)$ due to the correlation between prices and quantities, the price distribution is asymmetric.

Hence, in addition to the average spread, we have to compare the amplitude of food price fluctuations above and below the mean value. This can be done using the upper and lower limits of the confidence intervals of food prices. Denoting by $y_d^\gamma(z)$ and $y_u^\gamma(z)$ the lower and upper bounds of the confidence interval of the production of crop z at confidence level $1-\gamma$, the corresponding price bounds are derived from $L\tilde{x} = \tilde{y}$ and (10), which give $\Pr[y_d^\gamma(z) \leq \tilde{y}(z) \leq y_u^\gamma(z)] = \Pr[p_d^\gamma(z) \leq \tilde{p}(z) \leq p_u^\gamma(z)]$ where $p_u^\gamma(z) \equiv \alpha(z)(1-b)LR/y_d^\gamma(z)$ and $p_d^\gamma(z) \equiv \alpha(z)(1-b)LR/y_u^\gamma(z)$. Because production distributions are symmetric, $y_d^\gamma(z)$ and $y_u^\gamma(z)$ are equally distant from $y(z)$. However, since prices and quantities are inversely related, this is not the case for $p_d^\gamma(z)$ and $p_u^\gamma(z)$. The following proposition completes these general features of the price distributions with some useful approximations.

Proposition 7 *The expected value and the standard deviation of crop prices are approximated by*

$$p(z) \approx \bar{p}(z)[1 + v(\tilde{y}(z))^2] \tag{42}$$

and

$$\sigma(\tilde{p}(z)) \approx \bar{p}(z)v(\tilde{y}(z))\sqrt{1 - v(\tilde{y}(z))^2}.$$

Confidence intervals at confidence level $1-\gamma$ *are delimited by* $p_u^\gamma(z) = p(z) + s_u^\gamma\sigma(\tilde{p}(z))$ *and* $p_d^\gamma(z) = p(z) + s_d^\gamma\sigma(\tilde{p}(z))$ *with*

$$s_u^\gamma \approx \frac{v(\tilde{y}(z)) + s_\gamma}{[1 - s_\gamma v(\tilde{y}(z))][1 - v(\tilde{y}(z))^2]^{1/2}} \tag{43}$$

and

$$s_d^\gamma \approx \frac{v(\tilde{y}(z)) - s_\gamma}{[1 + s_\gamma v(\tilde{y}(z))][1 - v(\tilde{y}(z))^2]^{1/2}} \tag{44}$$

where $s_\gamma \equiv \Phi^{-1}(1-\gamma/2)$, Φ *being the cumulative distribution function of the standard normal distribution. Bounds of the confidence interval of the price of crop* z *are approximately equal to*

$$p_u^\gamma(z) \approx \bar{p}(z)\left[1 + v(\tilde{y}(z))^2 + v(\tilde{y}(z))\frac{v(\tilde{y}(z)) + s_\gamma}{1 - s_\gamma v(\tilde{y}(z))}\right] \tag{45}$$

and

$$p_d^{\gamma}(z) \approx \bar{p}(z)\left[1 + v(\tilde{y}(z))^2 + v(\tilde{y}(z))\frac{v(\tilde{y}(z)) - s_\gamma}{1 + s_\gamma v(\tilde{y}(z))}\right]. \tag{46}$$

Proof: see the appendix.

Because prices and quantities are inversely related, we have $s_d < s_u$, i.e the price distribution is skewed to the right: its right tail is longer and fatter than its left tail. The consequences on food price volatility are that the chances that a crop price is very low compared to the expected price, i.e., $\tilde{p}(z) \leq \bar{p}(z) < p(z)$, are larger than the chances of a high price, i.e. $\tilde{p}(z) > p(z)$, since $1/2 = \Pr[\tilde{p}(z) \geq \bar{p}(z)] > \Pr[\tilde{p}(z) > p(z)]$. However, the possible range of high prices is wider than the range of low prices: $p_u(z) - p(z) > p(z) - p_d(z) > \bar{p}(z) - p_d(z)$. Hence, the production volatility may cause rare but large food price spikes.[26]

Figures 1 and 2 illustrate these findings. The solid curves with the marks depict the crop average price in each case as indicated (depicted are Home's autarky prices). The corresponding dashed curves depict the approximate values of $p_d(z)$ and $p_u(z)$. The vertical distance between these curves corresponds to a confidence interval at level equal to 95%. Compared to under autarky, the non-strategic average prices are larger for more than 70% of crops, and the confidence intervals are very large. This is due to the tightening of the pesticides regulations mentioned above. The strategic effects that loosen these regulations induce lower average prices and confidence intervals. Biodiversity effects are reflected in Fig. 2 by strategic and non-strategic average price curves that encompass a flat portion around $z = 1/2$ which corresponds to the mix-production range. Confidence intervals over these ranges are smaller the closer the crop is to $z = 1/2$.

5. Comparative assessments

To illustrate the impact of biodiversity effects on food productions and prices, we summarize in this section the results of numerical comparative static exercises. These simulations allow us to assess the way the biodiversity effects and potential yield differentials affect the trade pattern, the environmental tax policy and the food price behavior. The effects on food prices are captured through a price index defined as $\int_0^1 p(z)y(z)dz \Big/ \int_0^1 y(z)dz$.[27]

[26] The asymmetry of price fluctuations, and their amplitude, depend on the convexity of the demand function. Indeed, the condition $p_u(z) - p(z) > p(z) - p_d(z)$ is equivalently written $p(z) < [p_u(z) + p_d(z)]/2$, with $[p_u(z) + p_d(z)]/2 = [D^{-1}(y_d(z)) + D^{-1}(y_u(z))]/2$, where D is the demand function. As $p(z) > \bar{p}(z) = D^{-1}(y(z))$ where $y(z) = [y_d(z) + y_u(z)]/2$, a necessary condition is $D^{-1}([y_d(z) + y_u(z)]/2) \leq [D^{-1}(y_d(z)) + D^{-1}(y_u(z))]/2$, hence $D^{-1}(y)$ must be convex from the Jensen's inequality.

[27] Details on the way the food price index is approximated are given in the appendix. Tax levels reported in the table are expressed as a percentage of production costs τ/c (c is the same whatever the case at hand). Also, a food price index of 2 means that the average price of agricultural goods equals 2% of the industrial goods

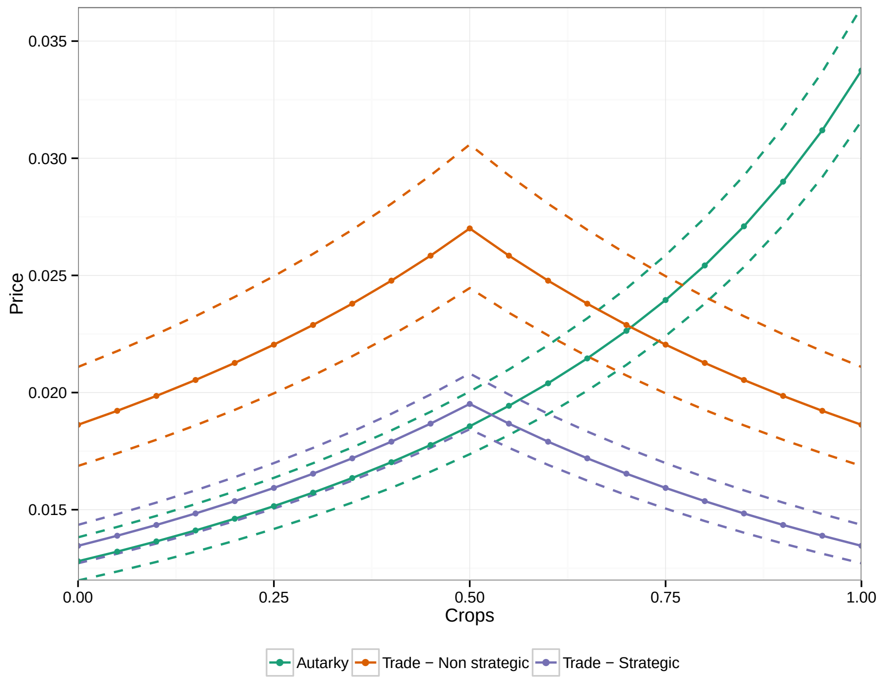

Figure 1 – Average prices and price volatility (confidence interval at 95% confidence level) without biodiversity effects. κ **= 0**, N**=100**, $h = 10^{-3}$, $b = 0.8$, $\ell = 20$, $m = 0.45$, $\mu = 1$, $a(1/2) = 29$.

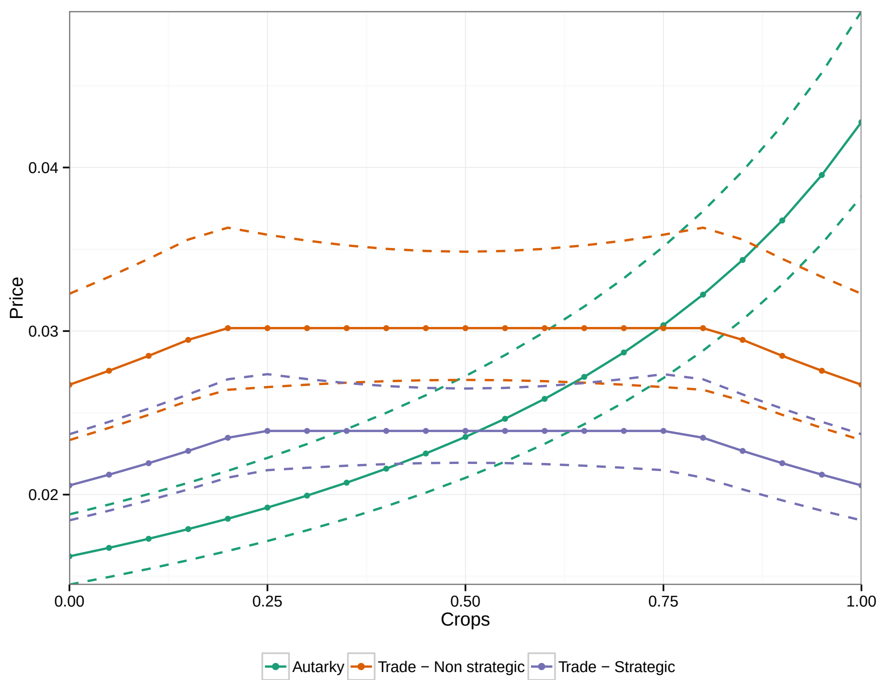

Figure 2 – Average prices and price volatility (confidence interval at 95% confidence level) with biodiversity effects. κ **= 0.3**, N**=100**, $h = 10^{-3}$, $b = 0.8$, $\ell = 20$, $m = 0.45$, $\mu = 1$, $a(1/2) = 29$.

The left part of table 1 summarizes the impacts due to the biodiversity effects: the larger κ is, the larger the negative impact of the cultivation intensity on the survival probability of plots. Biodiversity effects play against the specialization induced by trade: the range of crops produced by both countries increases when κ rises. Since biodiversity effects impede production, prices increase with κ as shown by the trend in the food price index reported in table 1. The larger κ is, the more effective pesticides are in reducing the negative externality due to the cultivation intensity and, therefore, the lower the environmental tax. Nevertheless, pesticides do not allow farmers to eradicate the biodiversity effect. Thus, even if more pesticides are applied when κ increases, the food price volatility increases. The tax on pesticides is more stringent under trade than under autarky, even when trade is strategic, for the reasons detailed above. In our simulations, non strategic taxes are more than 58% higher than strategic ones. Food price index levels reported in table 1 show that the decrease in food prices due to trade is lower the larger the biodiversity effects. The ratio between the VC levels at $z = 1/2$ of the worldwide production and the domestic production under autarky gives the size of the scale effect on prices (e.g. for $\kappa = 0.1$, it corresponds to 5.46/8.62=63.3% which is lower than on the production side $\sqrt{2}/2 \approx 70.7\%$). The yield effect is maximum for crop $z = 0$: for $\kappa = 0.1$, it corresponds to an additional (6.24-5.46)/8.62=9%. Table 1 also illustrates that the price volatility increases for crops produced by both countries even for small values of κ because of the significant increases in the environmental tax under strategic trade compared to under autarky: even for $\kappa = 0.1$, the volatility of the specialized crops (7.07%) is larger than under autarky (6.24%).

The right hand side of table 1 describes the impact of the potential crop yield differentials: the larger m is, the larger the difference in the potential yield of each crop (away from $z = 1/2$), and the greater the difference in comparative advantages of the two countries. The range of crops that are produced by both countries under free trade ($\bar{z} - \underline{z}$) decreases with m. Effects of m on the environmental tax depend on whether trade is strategic or not. Under non strategic trade, the impact of the environmental policy on consumer welfare goes through the food prices only. Therefore, the larger m is, the larger the specialization and the lower the tax on pesticides. Under strategic trade, the use of pesticides may have a significant impact on the market share of the country, particularly when comparative advantages are sufficiently close. This is reflected in table 1: the smaller m is, the lower the environmental tax. The way the food price index varies with m also differs between the non strategic and the strategic case. Two effects play on the quantities produced: on

price. The variation coefficient of domestic crop prices is the same for all crops under autarky. Worldwide variation coefficients indicated under autarky are derived from a fictitious price distribution corresponding to the sum of Home and Foreign productions. Worldwide variation coefficients evolve between minimum value $v(\tilde{p}^W(1/2))$ and maximum values $v(\tilde{p}^W(0))$ (autarky) and $v(\tilde{p}^W(\underline{z}))$ (trade).

Table 1 – Sensitivity analysis on parameters κ and m

	Values of κ (m=0.6)					Values of m (κ = 0.1)			
Variables (%)	0.1	0.3	0.5	0.7	0.9	0.2	0.4	0.6	0.8
Autarky									
τ/c	45.46	40.15	37.07	35.05	33.61	45.46	45.46	45.46	45.46
Food price index	2.03	2.38	2.73	3.09	3.45	2.03	2.03	2.03	2.03
$v(\tilde{p}(\cdot))$	8.62	10.10	11.39	12.53	13.57	8.62	8.62	8.62	8.62
$v(\tilde{p}^W(1/2))$	5.46	6.29	6.99	7.60	8.14	5.46	5.46	5.46	5.46
$v(\tilde{p}^W(0))$	6.24	7.16	7.94	8.61	9.20	5.55	5.83	6.24	6.76
Non strategic trade									
τ/c	83.29	73.23	69.03	66.49	64.68	86.02	83.94	83.29	82.97
Food price index	2.28	2.83	3.35	3.85	4.32	2.70	2.47	2.28	2.12
$v(\tilde{p}^W(1/2))$	8.00	8.84	9.76	10.62	11.42	8.19	8.05	8.00	7.98
$v(\tilde{p}^W(\underline{z}))$	8.82	10.61	12.19	13.55	14.75	9.02	8.87	8.82	8.80
$\bar{z}-\underline{z}$	20.66	46.96	64.70	77.69	87.65	63.23	31.13	20.66	15.46
Strategic trade									
τ/c	52.51	44.83	40.99	38.53	36.76	46.82	49.83	52.51	54.81
Food price index	1.77	2.25	2.68	3.08	3.46	2.00	1.88	1.77	1.68
$v(\tilde{p}^W(1/2))$	6.39	7.37	8.28	9.10	9.85	6.18	6.29	6.39	6.49
$v(\tilde{p}^W(\underline{z}))$	7.07	8.91	10.42	11.70	12.84	6.84	6.96	7.07	7.17
$\bar{z}-\underline{z}$	17.16	41.51	58.71	71.64	81.76	50.19	25.43	17.16	13.01

N=100, $h=10^{-3}$, $b=0.8$, $\ell=20$, $\mu=0.7$, $a(1/2)=290$.

the one hand, when m raises, the productivity increases and, on the other hand, when the environmental tax increases, the quantities produced decrease. In the non strategic case, when m increases, the tax decreases. Then, the two effects go in the same direction, the quantities produced increase and prices decline. Under strategic trade, m and the environmental tax both increase, their effects are countervailing on the quantities produced. The impact of the increase in the productivity prevails and the food price index decreases, even if the environmental tax is raised. Finally, in both strategic and non strategic cases, price volatility increases when the use of pesticides declines, i.e. when the environmental tax raises.

6. Conclusion

Biodiversity effects create diseconomies of scale (external to farms) in the agricultural sector. The more food production is specialized on a few high-yield crops, the higher are marginal costs of production, because of higher quantities of pesticides needed and/or lower yields. In a Ricardian trade model involving two countries differing only in their potential crop yields, these diseconomies result in an incomplete specialization. This pattern of trade affects the taxation policies adopted by governments that want to limit the negative impact of pesticides on the environment and human health. Indeed, incomplete specialization reduces comparative advantages and therefore reinforces NIMBY considerations leading to stricter environmental polices under free trade than under autarky. Hence, free trade does not necessarily lead to a race to the bottom on environmental policies. Reducing the use of pesticides causes nevertheless an increase in yield variability which translates in more volatile food prices. The mechanisms we describe in this paper are not highly visible today in food markets, since the massive use of pesticides reduces and almost cancels the impact of pests on yields and prices. However, concerns about the negative externalities of pesticides and the weight of NIMBY considerations in public decisions are raising, as testified, for example, by the growing share of farmland devoted to organic farming. Biodiversity impacts on price volatility could become larger and gain importance over the impacts of demand variability and stock management. In this context, gaining some insights in the mechanisms at stake is of growing importance for policymakers. Our analysis makes these mechanisms apparent in a very simple context, which allows to clearly identify them, but a comprehensive assessment supposes a more detailed and realistic representation of the worldwide food trade. This could be permitted by the setup developed by Eaton and Kortum (2002) and applied to agricultural trade by Costinot and Donaldson (2012) and Costinot et al. (2012). While these studies incorporate a stochastic component to determine the pattern of trade, it is not related to the production process and somehow arbitrary. Our analysis offers an interesting route to ground these approaches at least in the case of agricultural products. Also, accounting for these biodiversity effects should allow for a better appraisement of the importance of trade costs in determining the pattern of food trade.

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Appendix

A. Proof of Proposition 1

For given t, t^*, c, c^*, (15) and (16) define a system of two linear equations with two unknowns. Solving this system gives (19). By definition of threshold crops $\underline{z}$ and $\bar{z}$, we must have $B(z) = 0$ for all $z \geq \bar{z}$ and $B^*(z) = 0$ for all $z \leq \underline{z}$. This implies that we must have $\phi(z) \geq 1/q$ or all $z \geq \bar{z}$ and $\phi^*(z) \geq 1/q^*$ for all $z \leq \underline{z}$. Differentiating (20) and its counterpart for Foreign, we get

$$\dot{\phi}(z) \equiv \frac{\phi'(z)}{\phi(z)} = \frac{A'(z)}{t^*/t + A(z)} - \frac{t^*\kappa\alpha'(z)}{1 + t^*\alpha(z)\kappa}$$

and

$$\dot{\phi}^*(z) = -\dot{A}(z) + \frac{A'(z)}{t^*/t + A(z)} - \frac{t\kappa\alpha'(z)}{1 + t^*\alpha(z)\kappa}.$$

Suppose $\kappa = 0$: As $\dot{A}(z) > 0$, we have $\dot{\phi}(z) = A'(z)/[t^*/t + A(z)] > 0$ and $\dot{\phi}^*(z) = -\dot{A}(z)(t^*/t)/[t^*/t + A(z)] < 0$. Both conditions are thus satisfied if κ is sufficiently small. They are also satisfied whatever the value of κ if $\alpha(z)$ is constant as supposed in the symmetric case. Eq. (17) and (18) are derived from $\phi(\bar{z}) = 1/q$ and $\phi^*(\underline{z}) = 1/q^*$ respectively. Using these equations, we obtain $A(\bar{z})/A(\underline{z}) = [q^* + t^*\kappa\alpha(\bar{z})][q + t\kappa(\underline{z})\alpha(\underline{z})]/(qq^*) > 1$. As $A(z)$ is increasing, we thus have $\bar{z} > \underline{z}$.

B. Proof of Proposition 3

Using (23) which simplifies to

$$\bar{p}_s(z) = \frac{2(\ell - 1)(1 - b)tq}{ba(z)}$$

and denoting by ϖ the Lagrange multiplier associated with the constraint, the first-order condition with respect to t gives

$$-(1 - b)q + \frac{Nh}{\sqrt{2 \ln t}} - \varpi \frac{1}{\xi'(z_s)} \frac{t^*}{t} = 0$$

and the one with respect to q

$$\varpi = \frac{2(1 - b)}{b + 2q(1 - b)}.$$

Plugging the latter expression into the former and rearranging terms gives (31). At a symmetric equilibrium, using $\xi'(z_s) = A'(1/2) + 4$ and $\tau_A/c_A = Nh/(1-b)$, we get

$$\frac{\tau}{c} = \frac{\tau_A}{c_A}\left[1 + \frac{A'(1/2)}{A'(1/2)+8}\right]$$

where $c = c_A$. We thus have

$$\tau = \tau_A\left[1 + \frac{A'(1/2)}{A'(1/2)+8}\right].$$

Denoting $M \equiv A'(1/2)$, we get $\lim_{M\to 0} \tau = \tau_A$, $\lim_{M\to+\infty} \tau = 2\tau_A$ and

$$\frac{d\tau}{dM} = \frac{8\tau_A}{(M+8)^2} > 0.$$

C. Proof of Proposition 4

Differentiating (28) with respect to t, we obtain the following FOC

$$\frac{\partial V}{\partial t} = -(1-b)\left[\underline{z}\frac{q+2t\kappa}{t(q+t\kappa)} + \frac{(\bar{z}-\underline{z})(q^*+t^*\kappa)}{q(t^*-t)+t(1+t^*\kappa)} - \int_{\underline{z}}^{\bar{z}} \frac{A(z)/t^* - t^*/t^2}{A(z)t/t^* + t^*/t}dz\right] - h\frac{dZ}{dt}.$$

At a symmetric equilibrium, using $(A(z)-1)/(A(z)+1) = m(2z-1)$ and integrating gives (36). Using (35) in (36) and collecting terms, we arrive at

$$\frac{\partial V}{\partial t} = \frac{Nh}{t\sqrt{2\ln t}} - (1-b)\left[\frac{1}{2t} + \kappa\frac{2m(1+t\kappa)^2 - t\kappa}{2m(1+2t\kappa)(1+t\kappa)^2}\right].$$

Denote by t_0 the optimal tax when there is no cross-externality effects, i.e. $\kappa = 0$. It verifies (30) where $q = 1/2$. We have

$$\left.\frac{\partial V}{\partial t}\right|_{t=t_0} = -(1-b)\kappa\frac{2m(1+t_0\kappa)^2 - t_0\kappa}{2m(1+2t_0\kappa)(1+t_0\kappa)^2}$$

which is positive if

$$m \leq \frac{t_0\kappa}{2(1+t_0\kappa)^2} \leq 1/8.$$

We also have

$$\begin{aligned} \frac{1}{1-b}\left.\frac{\partial V}{\partial t}\right|_{t=t_A} &= \frac{1}{2t_A} + \frac{\kappa}{1+t_A\kappa} - \kappa\frac{2m(1+t_A\kappa)^2 - t_A\kappa}{2m(1+2t_A\kappa)(1+t_A\kappa)^2} \\ &= \frac{1}{2t_A} + \frac{t_A\kappa^2}{1+t_A\kappa}\frac{2m(1+t_A\kappa)+1}{2m(1+2t_A\kappa)(1+t_A\kappa)} > 0 \end{aligned} \quad (47)$$

hence $t > t_A$ at the optimum.

D. Proof of Proposition 5

At a symmetric equilibrium (37) simplifies to

$$\frac{\partial V}{\partial q} = 2(1-b) + 2(1-b)\frac{1-(\bar{z}+\underline{z})}{1+2t\kappa}$$

where $\bar{z}+\underline{z}=1$, hence $\partial V/\partial q = 2(1-b)$. We also obtain using (29) that at a symmetric equilibrium

$$\frac{dq}{dt} = -\frac{\frac{2(1+t\kappa)}{t}\int_{\underline{z}}^{\bar{z}}\frac{A(z)}{[A(z)+1]^2}dz - \frac{1}{2t}\int_{\underline{z}}^{\bar{z}}\frac{A(z)}{A(z)+1}dz}{t\kappa+\bar{z}-\underline{z}}.$$

Denoting $m_0=(m+1)/2$, using

$$\begin{aligned}\int_{\underline{z}}^{\bar{z}}\frac{A(z)}{[A(z)+1]^2}dz &= \int_{\underline{z}}^{\bar{z}}[m_0-mz-(m_0-mz)^2]dz\\ &= (\bar{z}-\underline{z})(m_0-m/2)+\frac{(m_0-m\bar{z})^3-(m_0-m\underline{z})^3}{3m}\\ &= \frac{t\kappa}{2m(1+t\kappa)}\frac{2(1+t\kappa)^2+1+2t\kappa}{6(1+t\kappa)^2}\end{aligned}$$

and

$$\int_{\underline{z}}^{\bar{z}}\frac{A(z)}{A(z)+1}dz = \int_{\underline{z}}^{\bar{z}}(1-m_0+mz)dz = (\bar{z}-\underline{z})(1-m_0+m/2) = \frac{t\kappa}{2m(1+t\kappa)}$$

yields (38). Differentiating, we get

$$\frac{dq^2}{dtd\kappa} = -\frac{(4-m)(1+t\kappa)^2+4m(1+t\kappa)+2}{12(1+t\kappa)^2[m(1+t\kappa)+1]^2} < 0.$$

Using (47) we obtain

$$\frac{1}{1-b}\left.\frac{dV}{dt}\right|_{t=t_A} = \frac{1}{2t_A}+\frac{t_A\kappa^2[2m(1+t_A\kappa)+1]}{2m(1+2t_A\kappa)(1+t_A\kappa)^2}-\frac{3+9t_A\kappa+4(t_A\kappa)^2}{6t_A(1+t_A\kappa)[m(1+t_A\kappa)+1]} \quad (48)$$

where the second term diverges when m tends to 0 and decreases with m while the last term increases with m (decreases in absolute value). Assuming that m is large enough and $\kappa\approx 0$, we have

$$\begin{aligned}\frac{1}{1-b}\left.\frac{dV}{dt}\right|_{t=t_A} &= \frac{1}{2t_A}-\frac{1+3t_A\kappa}{2t_A[m(1+2t_A\kappa)+1+t_A\kappa]}+o(\kappa)\\ &= \frac{1}{2t_A}\left[\frac{m(1+2t_A\kappa)-2t_A\kappa}{m(1+2t_A\kappa)+(1+t_A\kappa)}\right]+o(\kappa)\end{aligned}$$

where the bracketed term is negative if

$$m < \bar{m} \equiv \frac{2t_A\kappa}{1+2t_A\kappa}.$$

However, as the second term of (48) diverges when m approaches 0, we cannot neglect this term unless m is above some threshold $\underline{m} > t_A\kappa/(1+t_A\kappa)$. Indeed, in the case where $m = t_A\kappa/(1+t_A\kappa)$, we have

$$\begin{aligned} \frac{1}{1-b}\left.\frac{dV}{dt}\right|_{t=t_A} &= \frac{1}{2t_A} + \frac{\kappa}{2(1+t_A\kappa)} - \frac{3+9t_A\kappa+4(t_A\kappa)^2}{6t_A(1+t_A\kappa)^2} \\ &= \frac{(t_A\kappa)^2}{3t_A(1+t_A\kappa)^2} > 0. \end{aligned}$$

Hence, assuming κ is small enough, cases where the environmental tax at equilibrium is lower than under autarky correspond to $m \in [\underline{m}, \bar{m}]$ where

$$\bar{m} - \underline{m} < \frac{2t_A\kappa}{1+2t_A\kappa} - \frac{t_A\kappa}{1+t_A\kappa} = \frac{t_A\kappa}{(1+t_A\kappa)(1+2t_A\kappa)} \le \frac{\sqrt{2}}{4+3\sqrt{2}} \approx 0.17.$$

E. Proof of Proposition 6

Without biodiversity effects, using (39) and (40) with $\kappa = 0$, we obtain that $v(\tilde{y}_A^W(z)) \ge v(\tilde{y}^W(z))$ iff

$$1 - \frac{4A(z)}{[1+A(z)]^2} \ge \frac{t-t_A}{t_A-\mu}.$$

As $A(z)/[1+A(z)]^2$ is cap-shaped with a maximum equal to 1/4 at $z = 1/2$, this condition is satisfied for all z only if $t = t_A$. With $t > t_A$, it could be satisfied for z belonging only to one of the extremes of the crops' range, i.e. for z either close to 0 or close to 1, if $t - t_A$ is small enough. With biodiversity effects, for $z \in [\underline{z}, \bar{z}]$, using (41) and assuming that $t \ge t_A$, we obtain that $v(\tilde{y}_A^W(z)) \ge v(\tilde{y}^W(z))$ iff

$$\frac{4A(z)}{[1+A(z)]^2} - 1 \ge \frac{t\kappa(1+t\kappa) - \kappa t_A(1+t_A\kappa)}{(1+t\kappa)^2 - \kappa t_A(1+t_A\kappa) + \mu\kappa}$$

which is impossible unless $t = t_A$ and $z = 1/2$ since the last term is positive. For all $z \in [0, \underline{z}] \cup [\bar{z}, 1]$, using (39), we have $v(\tilde{y}_A^W(z)) \ge v(\tilde{y}^W(z))$ iff

$$2 - \frac{4A(z)}{[1+A(z)]^2} \ge \frac{t(1+2t\kappa)-\mu}{t_A(1+t_A\kappa)-\mu}.$$

A necessary condition is given by $2 > [t(1+2t\kappa)-\mu]/[t_A(1+t_A\kappa)-\mu]$, or re-arranging terms $t_A - \mu > (t - t_A)[1 + 2\kappa(t + t_A)]$ which is satisfied only if $t - t_A$ is not too large and κ sufficiently small.

F. Proof of Proposition 7

A second-order approximation gives

$$\begin{aligned}\tilde{p}(z) &= \frac{\alpha(z)(1-b)LR}{\tilde{y}(z)} \approx \frac{\alpha(z)(1-b)LR}{y(z)}\left[1 - \frac{\tilde{y}(z)-y(z)}{y(z)} + \left(\frac{\tilde{y}(z)-y(z)}{y(z)}\right)^2\right] \\ &= \bar{p}(z)\left[2 - \frac{\tilde{y}(z)}{y(z)} + \left(\frac{\tilde{y}(z)-y(z)}{y(z)}\right)^2\right]\end{aligned}$$

and thus

$$p(z) \approx \bar{p}(z)\left[1 + E\left(\frac{\tilde{y}(z)-y(z)}{y(z)}\right)^2\right] = \bar{p}(z)[1 + v(\tilde{y}(z))^2].$$

A first order approximation yields

$$\frac{E[(\tilde{p}(z)-\bar{p}(z))^2]^{1/2}}{\bar{p}(z)} \approx E\left[\left(1 - \frac{\tilde{y}(z)}{y(z)}\right)^2\right]^{1/2} = v(\tilde{y}(z)),$$

which gives

$$\begin{aligned}\sigma(\tilde{p}(z)) &\approx E\left[\tilde{p}(z) - \bar{p}(z) - \bar{p}(z)v(\tilde{y}(z))^2\right]^{1/2} = \left(E\left[(\tilde{p}(z)-\bar{p}(z))^2\right] - \bar{p}(z)^2 v(\tilde{y}(z))^4\right)^{1/2} \\ &= \bar{p}(z)v(\tilde{y}(z))(1 - v(\tilde{y}(z))^2)^{1/2}.\end{aligned}$$

From $p_u^\gamma(z) = p(z) + s_u^\gamma \sigma(\tilde{p}(z))$ we get

$$\begin{aligned}s_u^\gamma &\approx \frac{1}{\sigma(\tilde{p}(z))}\left(\frac{\alpha(z)(1-b)LR}{y(z) - s_\gamma \sigma(\tilde{y}(z))} - \bar{p}(z)(1 + v(\tilde{y}(z))^2)\right) \\ &= \frac{\bar{p}(z)}{\sigma(\tilde{p}(z))}\frac{y(z)(1 + v(\tilde{y}(z))^2) - y(z) + s_\gamma \sigma(\tilde{y}(z))}{y(z) - s_\gamma \sigma(\tilde{y}(z))} \\ &\approx \frac{y(z)v(\tilde{y}(z))^2 + s_\gamma \sigma(\tilde{y}(z))}{v(\tilde{y}(z))(1 - v(\tilde{y}(z))^2)^{1/2}(y(z) - s_\gamma \sigma(\tilde{y}(z)))} \\ &= \frac{v(\tilde{y}(z)) + s_\gamma}{(1 - v(\tilde{y}(z))^2)^{1/2}(1 - s_\gamma v(\tilde{y}(z)))}\end{aligned}$$

which gives (45). Similar derivations for $p_d^\gamma(z) = E[\tilde{p}(z)] - s_d^\gamma \sigma(\tilde{p}(z))$ yield (44) and (46).

G. Food Price Index

The food price index is defined as

$$F = \int_0^1 y(z)p(z)dz \Big/ \int_0^1 y(z)dz$$

where $p(z)$ is approximated by (42). As we also have $\bar{p}(z)y(z) = cNB(z)$, we get $p(z)y(z) \approx cNB(z)[1 + v(\tilde{y}(z))^2]$. In autarky, $c = (\ell - 1)(1 - b)/b$. Using $B(z) = 1$, $\theta(z) = \theta$, $\mu(z) = \mu$, and $y(z) = a(z)N/[t(1 + t\kappa)]$ gives

$$\int_0^1 p(z)y(z)dz = \frac{N(\ell - 1)(1 - b)}{b}\left[1 + \frac{t(1 + t\kappa) - \mu}{N\mu}\right].$$

Using $a(z) = \mu[1 - m(2z - 1)]$ yields

$$\int_0^1 y(z)dz = \frac{N}{t(1 + t\kappa)}\int_0^1 \mu[1 - m(2z - 1)]dz = \frac{N\mu}{t(1 + t\kappa)}$$

and thus

$$F_A = \frac{(\ell - 1)(1 - b)t(1 + t\kappa)}{b\mu}\left[1 + \frac{t(1 + t\kappa) - \mu}{N\mu}\right].$$

Under free trade, we have $\bar{p}(z)y(z) = 2N(l - 1)(1 - b)/b$. $B(z) = 2$ for crops produced by only one country and we get, using $\underline{z} + \bar{z} = 1$,

$$\int_0^{\underline{z}} p_s(z)y(z)dz + \int_{\bar{z}}^1 p_s(z)y^*(z)dz = \frac{4\underline{z}N(l - 1)(1 - b)}{b}\left[1 + \frac{t(1 + 2t\kappa) - \mu}{2\mu N}\right].$$

For crops produced by both countries we obtain

$$\int_{\underline{z}}^{\bar{z}} p_m(z)y_W(z)dz = \int_{\underline{z}}^{\bar{z}} \frac{2N(\ell - 1)(1 - b)}{b}\left[1 + \frac{(1 + t\kappa)(1 + 2t\kappa) - \mu\kappa}{2\mu N\kappa} - \frac{2(1 + t\kappa)^2}{\mu N\kappa}\frac{A(z)}{[1 + A(z)]^2}\right]$$
$$= \frac{2N(\ell - 1)(1 - b)}{b}\left\{\left[1 + \frac{(1 + t\kappa)(1 + 2t\kappa) - \mu\kappa}{2\mu N\kappa}\right](\bar{z} - \underline{z}) - \frac{t[2(1 + t\kappa)^2 + 1 + 2t\kappa]}{\mu N m 6(1 + t\kappa)}\right\}.$$

The corresponding quantities are given by

$$\begin{aligned}\int_0^{\underline{z}} y(z)dz + \int_{\bar{z}}^1 y(z)dz &= \frac{2N}{t(1 + 2t\kappa)}\left\{\int_0^{\underline{z}} a(z)dz + \int_{\bar{z}}^1 a^*(z)dz\right\} \\ &= \frac{2N\mu}{t(1 + 2t\kappa)}\left[\underline{z}(m + 1 - m\underline{z}) + 1 - \bar{z}(1 + m\bar{z} - m)\right]\end{aligned}$$

and

$$\int_{\underline{z}}^{\bar{z}} y_W(z)dz = \frac{N}{t(1+t\kappa)} \int_{\underline{z}}^{\bar{z}} [a^*(z) + a(z)]dz = \frac{2N\mu(\bar{z} - \underline{z})}{t(1+t\kappa)} = \frac{2N\mu\kappa}{m(1+t\kappa)^2}.$$

H. Fertilizers

Fertilizers can be easily introduced in our setting by considering that crop z's potential yield $\bar{a}(z)$ is the result of the intrinsic quality of land and the quantity of fertilizers spread on the field, $g(z)$. Denoting by $a_0(z)$ the potential crop z yield absent any treatment, we have $\bar{a}(z) = a_0(z)f(g(z))$ with $f(0) = 1, f'(g) > 0$ and $f''(g) < 0$. Total use of fertilizers, given by $G = N\int_0^1 B(z)g(z)dz$, has a negative impact on consumer welfare due to environmental damages. As pesticides, fertilizers have a direct positive impact on crop yields, but unlike pesticides, their productive impact is limited to the field they are spread on. Hence, the trade-off that defines the fertilizer policy is similar to the one of the pesticides regulation without biodiversity effects. While under autarky domestic consumers bear all the costs and reap all the benefits of the fertilizers used by their fellow farmers, this is no longer the case in free trade: they benefit from the crops produced abroad and share the advantages of a productive national sector with foreign consumers. As a result, restrictions on fertilizers are tighter under free trade than under autarky, with the same caveat as for pesticides: governments may use the fertilizer policy strategically. How lenient they are depends on the impact of fertilizers on relative yields: the more responsive is the relative yields function, i.e. the larger $f'(g)$, the lower the restrictions.