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Food Trade, Biodiversity Effects and Price Volatility*

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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 Classification Numbers: F18, Q17, Q18, Q56.

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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.¹ 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).² 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.³ These effects are 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)

¹See Gilbert and Morgan (2010) and Wright (2011) for overviews on food price volatility and examinations of the causes of recent price spikes.

²Oerke (2006) defines “potential loss” as losses occurring 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.

³The link between crop diversity and pests spreading has been widely investigated in the ecology literature, both theoretically and empirically. Zhu et al. (2000) is often cited for its empirical evidence of successful disease control in rice cultivation: in ten townships of the Yunnan province in China, thanks to a widespread crop diversification program conducted in 1998 and 1999 and mixing different genotypes of rice, the severity of rice panicle blast caused by a fungus was reduced by 94% and yield increased by 89% compared to monoculture. The effective role played by species diversity in limiting diseases and weeds dissemination has also been documented (Knops et al., 1999; Mitchell et al., 2002; Smith et al., 2008; Davis et al., 2012). For example, Smith et al. (2008) reports that in the absence of any pesticide use, yield doubled compared to monoculture thanks to diverse crop rotations.

⁴Pimentel (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).

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. This 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 develop a simple model of farm production affected by biotic factors that vary with specialization to represent the impacts of crop biodiversity on agricultural productivity and on the pattern of trade in a Ricardian two-country setup. We single out these impacts 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 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, when factor endowments of the countries are not too dissimilar, 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

⁵Correlatively, 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 nearly doubled between 2005 and 2016. 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.

⁶We elaborate on the effects of risk aversion in section 6.

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 two countries and many goods, à la Dornbusch et al. (1977, hereafter DFS). In this context, pests create external decreasing return to scale (DRS) in the agricultural sector that generate increasing marginal costs in a perfect competition setup. A number of papers have studied external economies of scale in Ricardian models. Ethier (1982) characterizes what Grossman and Rossi-Hansberg (2010) call “pathologies” generated by increasing returns to scale (IRS), in particular multiple equilibria and a reverse pattern of trade.⁹ With IRS, higher productivity leads to an increase in the industry scale which in turn improves productivity, creating a snowball effect responsible for these pathological results. To avoid these effects, Grossman and Rossi-Hansberg (2010) assume Bertrand competition.¹⁰ This is not necessary with DRS since the industry scale reduces productivity. However, the external scale effects we consider cause incomplete specialization. In this Ricardian setup, we find an impact of trade on the strength of environmental

⁷For 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).

⁸Weitzman (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).

⁹Indeed, with IRS, 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.

¹⁰Lyn and Rodríguez-Clare (2013) complete the setup by refining the way transport costs are taken into account.

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: when countries differ only in their potential crop yields, taxes under free trade are larger than under autarky.¹¹ 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 effects result in an incomplete specialization under free trade. Section 3 is devoted to the environmental policy. Optimal 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. We illustrate the biodiversity effects on the trade

¹¹Ricardian models have also been used in the so-called “North-South trade and the environment” literature that investigates the question of pollution havens created by trade (see e.g. Copeland and Taylor, 1994). In these models involving many countries with no significant market power, the environmental policy is not used as a strategic trade instrument.

between two asymmetric countries with numerical simulations calibrated on the US and Mexico data in section 5. Section 6 discusses the effects of risk aversion and section 7 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 DFS. Here, we consider two-sector economies (Home and Foreign) 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. 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.

2.1 Production

Our focus being on agriculture, the countries 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.¹² Home and Foreign are endowed with L units of labor and N land plots (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

¹²In order to streamline the analysis, we don't consider fertilizers. However, they can be easily incorporated in our model and the results are readily derived from the ones obtained on pesticides as explained in section 7.

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, 1999). 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

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

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 ,¹³ and c the other input costs, 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 $\bar{a}(z)$.¹⁴ 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, $\bar{\pi}(z)$.¹⁵ It also depends negatively on the share of land devoted nationally to

¹³This 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 .

¹⁴Pests 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.

¹⁵Indeed, 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.

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)

$$\bar{p}(z) \equiv \text{E}[\tilde{p}(z)\tilde{y}(z)]/\text{E}[\tilde{y}(z)] = p(z) + \text{cov}(\tilde{p}(z), \tilde{y}(z))/\text{E}[\tilde{y}(z)]. \quad (1)$$

Due to the correlation between total production $\tilde{y}(z)$ and market price $\tilde{p}(z)$, $\text{cov}(\tilde{p}(z), \tilde{y}(z)) < 0$, this reference price $\bar{p}(z)$ is lower than the expected market price. 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

$$\psi'(\pi(z); z, \pi(z), B(z)) = \tau/[\bar{a}(z)\bar{p}(z)]. \quad (2)$$

Assuming that the subsidy was set at $T(z) = \tau\pi(z)$ to allow farmers to break even at equilibrium,¹⁶ and that competition in the economy leads to $r(z) = 0$ for all z , we get

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

where $\psi(z) \equiv \psi(\pi(z); z, \pi(z), B(z))$ is the survival probability of a plot of crop z at equilibrium. As plots are identically and independently affected, we obtain that

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

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 by¹⁷

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

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.

¹⁶For 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.

¹⁷This functional form is a simplified version of a probabilistic model relying on a beta-binomial probability distribution and integrating externalities across all crops. For more details, see Bellora et al. (2017).

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 $\pi_i = \rho(z)$, the unregulated level of pesticides.¹⁸ 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

$$\pi(z) = \rho(z) - \tau/c, \quad (6)$$

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

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

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 tax index reaches a minimum equal to 1 in the absence of regulation, i.e. when the nominal tax τ is zero. Denoting the crop z maximum expected yield as $a(z) \equiv \bar{a}(z)\mu(z)$, the crop z average price is given by

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

and the expected domestic production level for crop z by

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

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.¹⁹ Section 4

¹⁸We assume in the following that $\kappa^* = \kappa$ and $\rho^*(z) = \rho(z) = \rho$, hence that pests and pesticides have the same effects on crops in Home and Foreign. We also normalize $\mu^*(z) = \mu(z) = \mu$ for all z so that comparative advantages are summarized by $A(\cdot)$ (without loss of generality).

¹⁹Denoting 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 $\text{Var}(\tilde{y}(z)) = \bar{a}(z)^2 \text{Var}(\tilde{X}(z))$, with $\text{Var}(\tilde{X}(z)) = NB(z)\psi(z)[1 - \psi(z)]$. Because $\psi(z)$ does not depend on N , the central limit theorem applies and the

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

$$U = b \ln x_I + (1 - b) \int_0^1 \alpha(z) \ln \tilde{x}(z) dz - hZ, \quad (10)$$

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 damages caused by a domestic use of

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

pesticides by farmers.²⁰ 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

$$\tilde{x}(z) = \alpha(z)(1 - b)R/\tilde{p}(z) \quad (11)$$

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 .²¹ We assume that consumers are risk-neutral and thus evaluate their *ex ante* welfare at the average consumption level of crop z , $x(z) \equiv E[\tilde{x}(z)]$.²² At market equilibrium under autarky (the same reasoning applies under free trade), as $L\tilde{x} = \tilde{y}$, we obtain from (1) and (11) that the volume-weighted average price $\bar{p}(z)$ is equal

distribution of $\tilde{X}(z)$ can be approximated by a normal distribution when N is large.

²⁰The disutility term hZ encompasses impacts due to exposure to pesticides, which includes environmental impacts as well as impacts on human health through direct (farmers) or indirect (rural populations) exposure. These latter impacts are well-known and appear to be the largest (Tago et al., 2014). We do not consider health impacts on consumers through pesticide residues in food which are much smaller and less documented (Winter and Davis, 2006), although they are found to be the second largest motivation for buying organic food after environmental concerns (Basha et al., 2015).

²¹We assume Cobb-Douglas preferences to ease computations, but similar effects as those described below could be obtained considering a CES utility function for food products, i.e. a utility of the form $U = (\int x(z)^{(\gamma-1)/\gamma} dz)^{\gamma/(\gamma-1)}$. Indeed, with a budget split in food and other expenditures in proportion $1 - b$ and b respectively, the demand for good z is similar to (11) but with a share $\tilde{\alpha}(z) = \tilde{p}(z)^{1-\gamma} / \int \tilde{p}(\omega)^{1-\gamma} d\omega$. Defining the food price index as $\tilde{P} \equiv (\int \tilde{p}(\omega)^{1-\gamma} d\omega)^{1/(1-\gamma)}$, (11) becomes $\tilde{x}(z) = (\tilde{p}(z)/\tilde{P})^{-\gamma} (1 - b)(R/\tilde{P})$ in which the nominal values are deflated by \tilde{P} .

²²We discuss the impact of risk aversion in section 6.

to $E[1/\tilde{p}(z)]^{-1}$. The representative consumer's indirect utility function can be written as²³

$$V = \ln(R) - (1 - b) \int_0^1 \alpha(z) \ln \bar{p}(z) dz - hZ. \quad (12)$$

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).²⁴ 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

$$LR = Nc_A + L - N. \quad (13)$$

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 if $\ell = \ell^*$ 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 (13) 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 is given by

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

²³Up to a constant given by $b \ln(b) + (1 - b) \int_0^1 \alpha(z) \ln \alpha(z) dz$.

²⁴Subscript "A" indexes equilibrium values under autarky.

The optimal tax index is determined by maximizing the utility of the representative consumer (12) 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. Since the per individual revenue is not affected by the environmental policy, this program only entails the tradeoff between the food price and the environmental quality. We obtain that the optimal tax index under autarky, t_A , solves

$$\sqrt{2 \ln t_A} \left[1 + \int_0^1 \frac{t_A \kappa \alpha(z)^2}{1 + t_A \kappa \alpha(z)} dz \right] = \frac{Nh}{1-b}. \quad (14)$$

The optimal tax is maximum for $\kappa = 0$, which corresponds to a nominal tax 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.

When $N = N^*$ and $L = L^*$, acreage and pesticides levels are the same in both countries under autarky. However, 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 DFS, 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.²⁵ 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

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

We obtain $Nc + N^*c^* = (L - N + L^* - N^*)(1 - b)/b$ and a total revenue given by

$$LR + L^*R^* = (L - N + L^* - N^*)/b.$$

²⁵Incomplete specialization is obtained in DFS 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.

As under autarky, the share of the agricultural sector of this revenue is unchanged, given by $1 - b$. The per-individual revenue for Home is given by

$$R(q) = \frac{Nc + L - N}{L} = \frac{L - N}{L} \left[1 + q \left(1 + \frac{L^* - N^*}{L - N} \right) \frac{1 - b}{b} \right], \quad (15)$$

where $q \equiv Nc/(Nc + N^*c^*)$ is the domestic share of the worldwide agricultural market obtained at equilibrium, which depends on crop yields 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.,

$$\begin{aligned} NB(z)c &= \alpha(z)(1 - b)(L - N + L^* - N^*)/b \\ &= \alpha(z)(Nc + N^*c^*) \end{aligned}$$

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):

$$\mathcal{A}(z) \equiv \frac{N^*}{N} A(z) = \frac{q^* t^*}{q t} \frac{1 + t^* \kappa B^*(z)}{1 + t \kappa B(z)}. \quad (16)$$

The second condition leads to

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

which can also be written as

$$\alpha(z) = qB(z) + q^*B^*(z). \quad (17)$$

Crop z is produced by both countries if there exist $B(z) > 0$ and $B^*(z) > 0$ that solve (16) and (17). 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*

$$\mathcal{A}(\bar{z}) = (t^*/t)[q^* + t^*\kappa\alpha(\bar{z})]/q \quad (18)$$

and

$$\mathcal{A}(\underline{z}) = (t^*/t)q^*/[q + t\kappa\alpha(\underline{z})]. \quad (19)$$

The intensity of these crops is given by

$$B(z) = \chi(z)[1/q - \phi(z)] \quad (20)$$

where

$$\phi(z) \equiv [1 + \mathcal{A}(z)t/t^*]/[1 + \alpha(z)t^*\kappa], \quad (21)$$

$$\chi(z) \equiv \frac{1 + t^*\alpha(z)\kappa}{t\kappa[\mathcal{A}(z)t/t^* + t^*/t]} \quad (22)$$

for Home and symmetric expressions hold for Foreign (with \mathcal{A} replaced by $1/\mathcal{A}$). 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 (18) and (19), we end up with $\mathcal{A}(\bar{z}) = \mathcal{A}(\underline{z}) = (q^*/q)(t^*/t)$ and thus a unique threshold index and complete specialization. With biodiversity effects, i.e. with $\kappa > 0$, we have $\mathcal{A}(\underline{z}) < \mathcal{A}(\bar{z})$ and since \mathcal{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*

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

and

$$y_T^W = \alpha(z) \frac{Na(z)t^*/t + N^*a^*(z)t/t^*}{qt^* + q^*t + \alpha(z)\kappa tt^*}$$

respectively. For these crops the break-even price is

$$\bar{p}_m(z) = \frac{(L - N + L^* - N^*)(1 - b)}{b} \frac{q(t^* - t) + t[1 + \alpha(z)t^*\kappa]}{N^*a^*(z)t/t^* + Na(z)t^*/t}. \quad (23)$$

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

$$\bar{p}_s(z) = \frac{1 - b}{b} \frac{L - N + L^* - N^*}{N} \frac{t[q + t\kappa\alpha(z)]}{a(z)} \quad (24)$$

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

$$Z_T = \frac{N}{q} \left\{ \int_0^{\underline{z}} \alpha(z)\rho(z)dz + \int_{\bar{z}}^{\infty} \chi(z)[1 - q\phi(z)]\rho(z)dz \right\} - N\sqrt{2 \ln t}. \quad (25)$$

Proof: direct from the preceding results.

These expressions depend on the environmental taxes and how the worldwide agricultural revenue is shared. To determine this sharing, we can use the fact that the domestic revenue comes from the sale of the goods produced nationally.²⁶ 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

$$q = \int_0^{\underline{z}} \alpha(z)dz + \int_{\bar{z}}^{\infty} s(z)\alpha(z)dz \quad (26)$$

where, using (4) and (17),

$$s(z) = \frac{y_T(z)}{y_T(z) + y_T^*(z)} = \frac{qB(z)}{qB(z) + q^*B^*(z)} = \frac{qB(z)}{\alpha(z)} \quad (27)$$

Replacing in (26) and using (20), we get

$$q = \frac{\int_0^{\underline{z}} \alpha(z)dz + \int_{\bar{z}}^{\infty} \chi(z)dz}{1 + \int_{\bar{z}}^{\infty} \phi(z)\chi(z)dz} \quad (28)$$

which also depends on t and t^* 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.

²⁶The same expression can be derived using the equilibrium condition on the land market.

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 is to maximize

$$W_{\kappa}(t, t^*) \equiv \ln(R) - (1-b) \left\{ \int_0^{\underline{z}} \alpha(z) \ln \bar{p}_s(z) dz + \int_{\underline{z}}^{\bar{z}} \alpha(z) \ln \bar{p}_m(z) dz + \int_{\bar{z}}^1 \alpha(z) \ln \bar{p}_s^*(z) dz \right\} - hZ \quad (29)$$

where $\bar{p}_s^*(z)$ is given by (24) with t and q replaced by t^* and $q^* = 1 - q$. The optimal tax index resulting from this program depends on t^* : maximizing (29) gives Home's best-response (BR) to Foreign's tax index t^* : $t = BR(t^*)$. Foreign's government is in the symmetric situation since both governments act simultaneously. At equilibrium, we have $t = BR(t^*)$ and $t^* = BR^*(t)$.

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 R , depends on environmental taxes.²⁷ 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 (26) yields, using $s(\bar{z}) = 0$ and $s(\underline{z}) = 1$,

$$\frac{dq}{dt} = q \frac{\int_{\underline{z}}^{\bar{z}} [B(z)(d\chi(z)/dt)/\chi(z) - \chi(z)(d\phi(z)/dt)] dz}{1 + \int_{\underline{z}}^{\bar{z}} \phi(z)\chi(z) dz} \quad (30)$$

where it is straightforward from (22) and (21) that $d\chi(z)/dt < 0$ and $d\phi(z)/dt > 0$. Hence, we have $dq/dt < 0$ and since $q + q^* = 1$, $dq^*/dt = -dq/dt > 0$. As shown below, strategic behavior results in a more intensive use of pesticides than non-strategic one.

To detail this competition effect and assess its interaction with the biodiversity externality that affects production, we consider in the following the case where the asymmetry between countries goes through the relative crop yields only: labor and land endowments are identical ($N^* = N$, $L^* = L$) to abstract to size effects, and $\alpha(z) = 1$ and $\rho(z) = \rho$ for all z , so that neither the demand nor the externality on consumers' utility distinguishes crops.²⁸ The total use of pesticides simplifies to $Z = N\rho - N\sqrt{2\ln t}$. We analyze the two

²⁷It 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.

²⁸Differences in factor endowments are analyzed through numerical simulations detailed in section 5.

types of free trade equilibria (non-strategic and strategic) assuming first that there is no biodiversity effects, 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 DRS in the agricultural sector at the national level.

3.1 Trade without biodiversity effects

As noted above, without any biodiversity effects, 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 in one segment of the range of crops delimited by threshold z_s which satisfies $A(z_s) = (q^*t^*)/(qt)$ using (16). 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 q solves $\xi(q) = t^*/t$ where $\xi(z) \equiv A(z)z/(1 - z)$ is strictly increasing.

In the non-strategic situation, governments ignore the effect of their environmental policy on the sharing of agricultural revenue. Neglecting the tax effects on q and R , (29) simplifies to

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

where q is considered as a constant. The first term corresponds to the tax impact on the price of crops produced locally and the second to its effect on pesticide use. The first-order condition leads to an optimal tax index that solves

$$\sqrt{2 \ln t} = Nh/[q(1 - b)]. \quad (31)$$

As $\sqrt{2 \ln t} = \tau/c$ and $c = 2qc_A$, (31) allows us to obtain $\tau = 2\tau_A$ whatever the country's share of the worldwide agricultural revenue.²⁹ We thus have the following result:

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

²⁹The fact that taxes at equilibrium are the same is due to the specifics of our model and the assumption that $\alpha(z) = 1$ and $\rho(z) = \rho$ for all z . Countries revenues depend on comparative advantages and are generally different.

pesticides used abroad, they want the use of pesticides restricted domestically in order to reduce pollution.³⁰ 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.³¹

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 (29), Home's best-response to t^* solves $\max_t W_0(t, t^*)$ where

$$W_0(t, t^*) = \ln(R(q)) - (1 - b) \left[\int_0^q \ln \bar{p}_s(z) dz + \int_q^1 \ln \bar{p}_s^*(z) dz \right] - hZ, \quad (32)$$

with $q = \xi^{-1}(t^*/t)$. It is shown in the appendix that it corresponds to t that solves

$$\sqrt{2 \ln t} \left[1 + \hat{R}(q) \varepsilon(q) / (1 - b) \right] = Nh / [q(1 - b)] \quad (33)$$

where $\hat{R}(q) = R'(q)/R(q)$ is the proportional change in income due to an increase in the domestic share of the food market, and $\varepsilon(q) = \xi(q)/[q\xi'(q)]$ is the elasticity of this market share with respect to the tax index.³² In terms of nominal tax, we get

$$\tau/\tau_A = 2(1 - b) / [1 - b + \hat{R}(q) \varepsilon(q)] \quad (34)$$

which shows that whatever the behavior of the other country, the domestic optimal nominal tax is reduced when the government takes the revenue effects into account.

To characterize the best-response function implicitly defined by (33), assume that

$$A(z) = A_0 [z/(1 - z)]^{1/\theta} \quad (35)$$

where $\theta \geq 1$ captures the strength of the comparative advantages (the higher the θ , the lower the productivity gaps) and $A_0 > 0$ is a dissymmetry parameter that affects positively the relative productivity of the foreign country (the case of $A_0 = 1$ corresponds

³⁰Markusen 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.

³¹Indeed, for any sharing $(q, 1 - q)$ of the agricultural production cost $2c_A$, the Pareto optimal tax level solves $\min_t 2(1 - b)q \ln t - hN(2 \ln t)^{1/2}$ for Home and the equivalent program for Foreign. Assuming symmetry, optimal production costs are equal, i.e. $q = 1/2$.

³²We have $\varepsilon(q) \equiv -(\Delta q/q)/(\Delta t/t) = (\Delta q/\Delta t)(t/q) = -1/\xi'(q) (-t^*/t^2) (t/q) = \xi(q)/[q\xi'(q)]$.

to symmetric advantages).³³ It is shown in the appendix that

$$\frac{\partial W_0}{\partial t} = \frac{1-b}{t} \left[\frac{Nh}{(1-b)\sqrt{2\ln t}} - \frac{2q(1-q)}{b+2q(1-b)} \frac{\theta}{1+\theta} - q \right] \quad (36)$$

and that a total differentiation of the first-order condition $\partial W_0/\partial t = 0$ yields

$$BR'(t^*) = - \frac{\partial^2 W_0}{\partial t \partial t^*} / \frac{\partial^2 W_0}{\partial t^2}$$

where

$$\frac{\partial W_0^2}{\partial t \partial t^*} = \frac{1-b}{\xi'(q)t^2} \frac{[\theta - (1+\theta)(1-b)][q(1-b)+b]4q - b[2\theta + b(1+\theta)]}{(1+\theta)[b+2q(1-b)]^2}.$$

Deriving the sign of this latter expression and verifying the second-order condition gives the following results

Proposition 3 *Suppose that there are no biodiversity effects and that the asymmetry between the two countries goes only through relative yields with $A(z) = A_0[z/(1-z)]^{1/\theta}$.*

Then,

- (i) $BR'(t^*)|_{q < q_s} < 0$ and $BR'(t^*)|_{q > q_s} > 0$ where $q_s > 1/2$.
- (ii) $\partial W_0^2/\partial t^2 \leq 0$ for all $\xi^{-1}(t^*/(BR(t^*))) > \underline{q} > 0$ with $\underline{q} < 1/2$ if $Nh < (1-b)\sqrt{2/b}$.
- (iii) $BR'(t^*)|_{q=1/2} > -1/A_0 > 1/BR'(t)|_{q=1/2}$ if $Nh < (1-b)\sqrt{b}$
- (iv) q_s and \underline{q} are independent of A_0 .

Proof: see the appendix.

From (i) the tax indexes t and t^* may be strategic substitutes or complements. More precisely, t may be increasing when t^* is very large (so that $q = \xi^{-1}(t^*/t) > q_s > 1/2$). From (ii), the optimal tax index cannot exceed a value that corresponds to a minimum, strictly positive, market share. The fact that this minimum value is lower than $1/2$ allows for a non-degenerate equilibrium at least in the symmetric case (which supposes $A_0 = 1$). The inequality involving Nh is a sufficient condition that guarantees that $\underline{q} < 1/2$ for all possible values of $\theta \geq 1$. It states that the extent of the negative impact of exposure to pesticides, given by h , should not be too large to avoid a NIMBY effect that would result in a complete prohibition of pesticide use in both countries at equilibrium. As stated in (iv), thresholds q_s and \underline{q} are not affected by A_0 , i.e. they are the same whatever the dissymmetry between the two countries. One reason is that in our general framework, the worldwide revenue to be split between the two countries is the same whatever the competitive advantages ($R(q)$ does not depend on the yield function directly). Another

³³Eq. (35) is obtained assuming, as in Eaton and Kortum (2002), that yields are distributed according to a Fréchet distribution. In our setup, this assumption corresponds to $\bar{a}(z) = (T/z)^{1/\theta}$ and $\bar{a}^*(z) = (T^*/(1-z))^{1/\theta}$, hence $A(z) = A_0 z^{1/\theta} (1-z)^{-1/\theta}$ where $A_0 \equiv (T^*/T)^{1/\theta}$.

reason is that in the specific case (35) the dissymmetry coefficient A_0 is a scale parameter which does not impact $\varepsilon(q)$, the elasticity of the market share with respect to the tax index. As a result, the marginal benefit of the environmental tax, (36), and the equivalent equation for Foreign, depends on θ only. However, the relationship $t^*/t = \xi(q)$ imposes a dependency between the ratio of the tax indexes and A_0 . Hence, while A_0 does not explicitly appear, Home's and Foreign's BRs are not symmetrical when $A_0 \neq 1$. Finally, (iii) allows us to compare the slopes of Home and Foreign BRs at (t, t^*) leading to equal market shares.

[Figure 1 about here.]

Figure 1 illustrates the symmetric case ($A_0 = 1$). Home's BR is depicted in red. All lines are expressed in Home's space referential (the x -axis and the y -axis are t^* and t respectively): e.g. the dashed line indicated as $t^*/\xi(q_s)$ corresponds to the equation $t = t^*/\xi(q_s)$. $BR(t^*)$ is first decreasing then increasing once it crosses the $t^*/\xi(q_s)$ line, i.e. for large values of t^* . $BR^*(t)$ follows an identical behavior in its referential. The slope of $BR(t^*)$ when crossing the $t^*/t = \xi(1/2) = A_0$ line, which corresponds to the bisector in the symmetric case, is flatter than the perpendicular to this line, whereas the slope of $BR^*(t)$ is steeper. As a result, $BR(t^*)$ crosses $BR^*(t)$ from below at the bisector, and thus they don't cross again under the condition $Nh < (1 - b)/\sqrt{b}$, which also guarantees that there is a symmetric equilibrium even when θ is very large.³⁴ When $q < \underline{q}$, the second-order conditions are not satisfied: the maximum value for the tax index is \bar{t} . Depictions of cases where $A_0 \neq 1$ would present the dashed lines with slopes identically affected (more or less steep than in the symmetric case) and the BRs would no longer be symmetric. However, as threshold values q_s and \underline{q} do not depend on A_0 , we would also have only one equilibrium and \bar{t} would not be affected.

The fact that the BRs are decreasing in the relevant part of their support suggests that Home finds it optimal to reduce its tax when Foreign increases its own. However, this intuition is misleading: Indeed, the game between the two countries is expressed as a competition in "real taxes", i.e. nominal taxes relative to the countries' revenues since the tax index t increases with the nominal tax τ and decreases with the market share q : we have $t = e^{(\tau/c)^2/2}$ where $c = 2qc_A$. As $\xi(q) = t^*/t = e^{[(\tau^*/q^*)^2 - (\tau/q)^2]/(8c_A^2)}$, simultaneous variations in $d\tau^*$ and $d\tau$ that do not affect q verify

$$\left. \frac{d\tau}{d\tau^*} \right|_{q=cst} = \frac{\tau^*}{\tau} \left(\frac{q}{1-q} \right)^2.$$

³⁴The condition for the existence of a symmetric equilibrium with pesticide use is less stringent: we must have $Nh < (1 - b)\sqrt{2/b}$. In the intermediate case $(1 - b)/\sqrt{b} < Nh < (1 - b)\sqrt{2/b}$, it may be the case that for some values of θ BR is steeper than BR^* , but there is still only one equilibrium whenever $\underline{q} \geq 1 - q_s$.

If Foreign increases τ^* , Home may react with an increase in τ smaller than this ratio so that its market share q increases more than proportionally, hence a ratio τ/q that decreases whereas τ^*/q^* increases. Consequently, an increase in τ^* may result in both an increase in τ and a decrease in t while t^* increases, in which case nominal taxes are strategic complements whereas tax indexes are substitutes.

To characterize the Nash equilibrium, we solve the first-order condition for q to obtain Home's desired share of the worldwide revenue corresponding to a tax index t (and similarly for Foreign). At equilibrium, these desired shares must be compatible, i.e. their sum must be equal to 1, and the corresponding ratio of tax indexes must correspond to the comparative advantages, i.e. $t^*/t = \xi(q)$. This leads to the following result:

Proposition 4 *Suppose that there are no biodiversity effects, that the asymmetry between the two countries goes only through relative yields, with $A(z) = A_0[z/(1-z)]^{1/\theta}$ and that $Nh < (1-b)/\sqrt{b}$. Then*

- (i) *Home's and Foreign's desired shares of the worldwide revenue corresponding to their tax indexes are given by the same function $Q(t)$ verifying $Q'(t) < 0$, $Q''(t) > 0$, $Q(t_A) = 1$, independent of A_0 and defined on the same support $[t_A, \bar{t})$ where $\bar{t} \equiv Q^{-1}(q)$.*
- (ii) *There is a unique pair of equilibrium strategies (t_N, t_N^*) that solves*

$$\begin{cases} 1 = Q(t_N) + Q(t_N^*) \\ t_N^*/t_N = A_0[Q(t_N)/Q(t_N^*)]^{(1+\theta)/\theta} \end{cases} \quad (37)$$

- (iii) *Denote $(t_N(A_0), t_N^*(A_0))$ the pair that corresponds to A_0 . For $A_0 \approx 1$ we have $t_N(A_0) > t_N(1) = t_N^*(1) > t_N^*(A_0)$ if $A_0 > 1$, and the reverse inequalities otherwise.*

Proof: see the appendix.

From (i), the desired shares of the two countries are given by the same function Q that depends on the strength parameter θ but not on the dissymmetry parameter A_0 (which does not appear in (36) for the reasons given above). Not surprisingly, this share function decreases with the tax index at a decreasing rate. The fact that $Q(t_A) = 1$ indicates that a country is willing to implement the same (low) tax index as under autarky if it captures the entire agricultural market. The Nash equilibrium that solves (37) corresponds to the crossing of the BR functions characterized above. There is one of such crossings for each value of A_0 . Point (iii) indicates that when a country has a larger probability of high yields, its tax index is lower than that of its rival: the relative increase in its share of revenue is larger than the one in the nominal level of its environmental tax (and symmetrically for the country that is less competitive): we have $\|\tau_N(A_0)/\tau_N(1) - 1\| < \|q/2 - 1\|$.

[Figure 2 about here.]

Figure 2 illustrates the derivation of the set of Nash equilibria. The first quadrant corresponds to the (t, t^*) plane. The set of Nash equilibria is depicted by the curve $T-T$ which is decreasing and convex (see the appendix). Corresponding tax indexes are greater than t_A (the autarky level) and lower than $\bar{t} = Q^{-1}(q)$, the largest tax value satisfying the second-order condition. The second and the fourth quadrant depict Foreign's and Home's desired share of worldwide revenue $Q(t^*)$ and $Q(t)$ in their respective plane (t^*, q^*) and (t, q) . Since these functions are the same, their curves are symmetrical with respect to the bisector. The third quadrant corresponds to the (q, q^*) plane. The compatibility condition $q + q^* = 1$ corresponds to the simplex. The bisector crosses the simplex at equal shares ($q = q^* = 1/2$) and the corresponding tax levels are deduced by following the blue arrows. Because the desired share functions are symmetrical, the tax indexes are the same and thus the Nash equilibrium corresponds to the blue dot located on the bisector in the (t, t^*) plane. The red arrows emanate from the simplex at a point where $q^* > 1/2 > q$. Following these red arrows, the corresponding Nash equilibrium is depicted by the red dot located above and to the left of the blue dot: Home tax index is thus larger than the one prevailing in the symmetrical case, whereas Foreign's is smaller. In any case, tax indexes are greater than their autarky level.

To isolate the impact of the strength of the comparative advantages, consider yield functions $A(z)$ that allow for a symmetric equilibrium. We then have $q = 1/2$, $t = t^*$, $A(1/2) = 1$ and using (35),

$$\tau = \tau_A [1 + 1/(1 + 2\theta)]$$

which shows that nominal tax under free trade is twice as large as the one under autarky (as in the non-strategic trade case) only if $\theta = 0$, and that this discrepancy reduces when the strength of comparative advantages decreases. However, in any case, $\tau > \tau_A$, which shows that the market share rivalry is not sufficiently strong to counteract the NIMBY effect.³⁵ We obtain a similar result in the general symmetric case:

Proposition 5 *Suppose that there are no biodiversity effects, that factor endowments are similar and that competitive advantages are symmetric. 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.*

³⁵The fact that the NIMBY effect dominates the strategic trade effect is reminiscent of DFS's analysis of a uniform technological shock on the trade equilibrium. Indeed, a decrease in the environmental tax of one country results in an increase in the productivity of its agricultural sector. The strategic trade component of the policy is similar to the change in the relative factor price in DFS (the land rent that determines the countries' market shares in our context) and the non-strategic component to the change in the domestic goods prices in DFS (the NIMBY effect in our context). As in DFS, the former is proportionally smaller than the latter.

Proof: see the appendix.

When comparative advantages are not too strong, 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 that interfere with the trade-off between the environmental concerns and the impacts on prices and market shares. On the one hand, as specialization provoked 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 tax affects the prices of a reduced set of crops, which should induce governments to increase it. To ease computations, we detail these effects using the following approximation of (35)

$$A(z) = A_0 \frac{\theta + 2(z - 1/2)}{\theta - 2(z - 1/2)} \quad (38)$$

and consider symmetric comparative advantages ($A_0 = 1$) in this section.³⁶ At a symmetric equilibrium, threshold crops given by (18) and (19) simplify to

$$\bar{z} = [1 + \theta t \kappa / (1 + t \kappa)] / 2 \quad (39)$$

and

$$\underline{z} = [1 - \theta t \kappa / (1 + t \kappa)] / 2. \quad (40)$$

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,

$$\bar{z} - \underline{z} = \theta t \kappa / (1 + t \kappa), \quad (41)$$

increases with κ , t and the strength of the competitive advantages θ .

In the non-strategic case, the condition that determines t at the symmetric equilibrium

³⁶A Taylor expansion of the function $x^{1/\theta}$ around $1/2$ gives

$$x^{1/\theta} \approx (1/2)^{1/\theta} + (1/\theta)(x - 1/2)(1/2)^{1/\theta - 1} = (1/2)^{1/\theta} [\theta + 2(x - 1/2)] / \theta$$

Replacing x by z and $1 - z$ in the numerator and the denominator of (35) respectively and simplifying gives (38).

is given by $(\partial W_\kappa / \partial t)_{t^*=t} = 0$ where

$$\frac{\partial W_\kappa}{\partial t} \Big|_{t^*=t} = -\frac{1-b}{t} \left[\frac{1+4t\kappa}{1+2t\kappa} \underline{z} + (\bar{z} - \underline{z}) \frac{1+2t\kappa}{2(1+t\kappa)} \right] - h \frac{dZ}{dt}. \quad (42)$$

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 (40) and (41), 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 (42). 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 6 *Suppose that the relative potential yield function is given by (38). 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 θ is very large. Overall, the environmental tax is larger than under autarky.*

Proof: see the appendix.

When the discrepancy in relative potential yields is large between the two countries (θ small), 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. It is shown in the appendix that this is always the case when θ is smaller than 8. However, when θ is very large (larger than a threshold which depends on the parameters

and which can be much larger than 8), each country produces a broad range of products. The cross-externality effect is less intense than in the case of perfect specialization and so is the need for pesticides. In any case, pesticide use is less intense than under autarky.

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

$$\frac{dW_\kappa}{dt} = \frac{\partial W_\kappa}{\partial t} + \frac{\partial W_\kappa}{\partial q} \frac{dq}{dt}$$

where

$$\frac{\partial W_\kappa}{\partial q} = \frac{2(1-b)}{b+2q(1-b)} - (1-b) \left[\frac{z}{q+t\kappa} - \frac{1-\bar{z}}{1-q+t^*\kappa} + \frac{(\bar{z}-z)(t^*-t)}{q(t^*-t)+t(1+t^*\kappa)} \right]. \quad (43)$$

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 $(\partial W_\kappa / \partial q)_{t^*=t, q=1/2} = 2(1-b)$. Using (38) and (30), we obtain that

$$\left. \frac{dq}{dt} \right|_{t^*=t, q=1/2} = - \frac{3+9t\kappa+4(t\kappa)^2}{12t(1+t\kappa)[(1+t\kappa)/\theta+1]} \quad (44)$$

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 that the optimal tax is larger than under autarky. We thus have the following result

Proposition 7 *Suppose that the relative potential yield function is given by (38). Then, at the symmetric strategic trade equilibrium, the environmental tax is smaller than the one at the non-strategic equilibrium. It is also smaller than the one in the case of $\kappa = 0$ if θ is not too large, and larger than the one 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 ?? 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: $v(\tilde{X}) \equiv \sigma(\tilde{X})/E(\tilde{X})$. 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 $\text{Var}(\tilde{y}(z)) = \bar{a}(z)^2 NB(z)\psi(z)[1 - \psi(z)]$. Using (7) and (9), the variation coefficient for the production by Home of a crop z is given by

$$v(\tilde{y}(z)) = \left\{ \frac{t[1 + t\kappa B(z)] - \mu(z)}{\mu(z)NB(z)} \right\}^{1/2}. \quad (45)$$

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

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

Using (7), we get

$$v(\tilde{y}_A^W(z)) = \left\{ 1 - \frac{2A(z)}{[1 + A(z)]^2} \right\}^{1/2} \left\{ \frac{t_A[1 + t_A\kappa\alpha(z)] - \mu(z)}{\mu(z)N\alpha(z)} \right\}^{1/2}. \quad (46)$$

While the second bracketed term in (46) is similar to (45), 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.³⁷

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 $\text{Var}(\tilde{y}_T^W(z)) = \text{Var}(\tilde{y}_T(z)) + \text{Var}(\tilde{y}_T^*(z))$ and $v(\tilde{y}_T^W(z))^2 = s(z)^2v(\tilde{y}_T(z))^2 + s^*(z)^2v(\tilde{y}_T^*(z))^2$, which lead to

$$v(\tilde{y}_T^W(z)) = \left\{ \frac{(1 + t\kappa)(1 + 2t\kappa) - \mu\kappa}{2\mu N\kappa} - \frac{2(1 + t\kappa)^2}{\mu N\kappa} \frac{A(z)}{[1 + A(z)]^2} \right\}^{1/2}. \quad (47)$$

As with (46), 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 8 *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.

³⁷With 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 (11), 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 9 *The expected value and the standard deviation of crop prices are approximated by*

$$p(z) \approx \bar{p}(z)[1 + v(\tilde{y}(z))^2] \quad (48)$$

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

$$s_u^\gamma \approx \frac{v(\tilde{y}(z)) + s_\gamma}{[1 - s_\gamma v(\tilde{y}(z))][1 - v(\tilde{y}(z))^2]^{1/2}} \quad (49)$$

and

$$s_d^\gamma \approx \frac{v(\tilde{y}(z)) - s_\gamma}{[1 + s_\gamma v(\tilde{y}(z))][1 - v(\tilde{y}(z))^2]^{1/2}} \quad (50)$$

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

$$p_u^\gamma(z) \approx \bar{p}(z) \left[1 + v(\tilde{y}(z))^2 + v(\tilde{y}(z)) \frac{v(\tilde{y}(z)) + s_\gamma}{1 - s_\gamma v(\tilde{y}(z))} \right] \quad (51)$$

and

$$p_d^\gamma(z) \approx \bar{p}(z) \left[1 + v(\tilde{y}(z))^2 + v(\tilde{y}(z)) \frac{v(\tilde{y}(z)) - s_\gamma}{1 + s_\gamma v(\tilde{y}(z))} \right]. \quad (52)$$

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.³⁸

Figures 3 and 4 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. 4 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 $z = 1/2$.

[Figure 3 about here.]

[Figure 4 about here.]

5 The case of asymmetric countries

In this section, we depart from symmetric potential crop yields and identical factor endowments to illustrate the additional effects that are brought in by differences in the size of the countries. More precisely, we derive the impacts of trade on welfare under different environmental policies considering two countries with characteristics calibrated using US and Mexican data. According to the World Bank, the inverse shares of active population

³⁸The 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.

in the agricultural sector are $\ell = 62$ and $\ell^* = 8$ respectively.³⁹ Using the ratio of employment in agriculture, we obtain $N^*/N = 3$. We consider that preferences are identical in both countries and we use the average of the shares of revenue spent in industrial goods in the US (94%) and in Mexico (77%) to obtain $b^* = b = 85.5\%$.⁴⁰ For crop yields, we use $\theta = 8.11$ as estimated by Caliendo and Parro (2014) and the relative agricultural productivities (614.6 and 378.4 dollars per hectare in 2014 for the US and Mexico respectively) to obtain $T^*/T = 0.62$.⁴¹ We arbitrarily set $\rho = 3$ and, since more pesticides are needed in tropical climates than in temperated ones to achieve the same impact on pest populations, $\rho^* = 6$. The disutility of the domestic use of pesticides and the intensity of biodiversity effects on crop production are unknown. We consider $h = 0.01$ in the following and we choose two possible values for κ (0.08 and 0.16) to compare the impact of its variation on welfare. Autarky is the referential and three alternative scenarios under trade are considered: (i) Foreign does not react ($\tau^* = \tau_A^*$), (ii) Foreign drops its environmental policy ($\tau^* = 0$) and (iii) Foreign sets its environmental policy at its optimal level. In all scenarios, we compute the non strategic as well as the strategic response of the domestic country. The impact on welfare is decomposed into revenue, food prices and pesticide use effects. Results are presented in Table 1.

[Table 1 about here.]

Home's tax levels under non-strategic trade correspond to a more than threefold increase than under autarky whatever the scenario. Strategic behavior tends to reduce the tax, and this effect is stronger the higher the Foreign tax. Indeed, a decrease in the domestic tax is more effective in gaining market share when the tax abroad is high rather than low. As in the symmetric case, strategic effects do not annihilate the NIMBY ones. Likewise, Nash equilibria under non-strategic trade lead to the same qualitative results as in the symmetric case: taxes are higher than under autarky in both countries. Under strategic trade, asymmetric endowments introduce scale effects in the revenue that depend on the relative size of the agricultural sector in the two countries. Because of these scale effects, the market share elasticity of revenue is much larger in Foreign than in Home (Foreign has a large agricultural sector relative to its total economy). As a consequence, it is highly effective for Foreign to decrease its environmental tax to gain market share and increase its revenue. This effect dominates the NIMBY one and results in a decrease

³⁹Population shares are reported in the World Indicator Database by the variable SL.AGR.EMPL.ZS. We consider the 2015 values retrieved in November 2017.

⁴⁰USDA (Economic Research Service) <https://www.ers.usda.gov/data-products/food-expenditures.aspx>, retrieved in October 2017.

⁴¹In FAOSTAT nomenclature, productions are identified by codes 152 (Element) and 2051 (Item) and agricultural areas by codes 5110 (Element) and 6610 (Item). These values were retrieved in November 2017.

in the foreign tax (by 23% to 24%) under trade compared to autarky. For Home, its small market share strengthens NIMBY effects. Potential food market share for the Home as given by $Nc_A/(Nc_A + N^*c_A^*)$ under autarky represents 75% of the total food market. However, the effective share q under free trade varies between 26% and 28% in the numerical simulations. This discrepancy is due to the increase in the environmental tax motivated by NIMBY considerations that are particularly strong since Foreign imposes low taxes in all the scenarios. Lastly, the range of crops produced by both countries is the smallest under strategic trade (the government maximizes its market share, which tends to reduce the range of crops produced by both countries), around 1% smaller than under non-strategic trade.

Since Home increases its tax in all scenarios, the welfare effect of pesticide use is improved (e.g. by around 7% under non-strategic trade with respect to autarky). This improvement is smaller under strategic than under non-strategic trade (by around 5 to 7%). The impact of taxes on prices is stronger than the decrease due to the redistribution of crop production according to comparative advantages. As a result, the decrease in revenue and the food price increase are not compensated by better environmental quality: the total variation of welfare is systematically negative for Home. The environmental effect is partly determined by the value of parameter h , which has not been estimated in the literature. An increase in h reinforces NIMBY effects and results in a stricter environmental policy. However, simulations with larger values for h (five to ten times) lead to increases in the environmental quality that are not sufficient to compensate for the reduction in the other welfare components.

Not surprisingly, the larger κ , the lower the environmental tax. This impact occurs both under autarky and under trade, but not in the same proportion. The figures reported in Table 1, expressed as variations relative to autarky, encompass these two decreases. For instance, Home tax under non-strategic trade when $\tau^* = \tau_A^*$ decreases by 0.7% when κ doubles. Biodiversity effects play against the specialization induced by trade: the range of crops produced by both countries increases when κ rises (+48% under strategic Nash equilibrium).

6 Risk aversion

We have assumed so far that individuals are risk neutral. Supposing they are risk averse, price volatility is a concern that could lead governments to adjust their tax policy on pesticides. We analyze this problem in the following, assuming that financial markets are complete, i.e. that agents could trade a complete set of contingent claims on the outcome of each crop. Under this assumption, while crop production is uncertain, revenue

variations can be completely hedged and only food price volatility matters.⁴² Hence, since revenue risks can be completely hedged, the implication of risk aversion for the tax policy is only to address the crop price risk faced by consumers, in addition to the NIMBY and strategic trade concerns. We can investigate this problem in our setup by using the Arrow-Pratt approximation of the risk premium. As production risks are independent, the expectation of (10), which gives the expected utility of the representative consumer, simplifies to

$$EU = b \ln x_I + (1 - b) \int_0^1 \alpha(z) E[\ln \tilde{x}(z)] dz - hZ$$

in which the consumer's Von Neuman-Morgenstern utility is the constant relative risk aversion function $u = \ln$. By definition, the per crop risk premium $\zeta(z)$ satisfies $E[\ln \tilde{x}(z)] = \ln(x(z) - \zeta(z))$ and its Arrow-Pratt approximation is $\zeta(z) \approx \text{Var}[\tilde{x}(z)] / (2E[\tilde{x}(z)])$. As $\tilde{x}(z) = \tilde{y}_T^W(z)R / (R + R^*)$, we obtain

$$\zeta(z) \approx [b/2 + q(1 - b)] \text{Var}[\tilde{y}_T^W(z)] / (2y_T^W(z)) \quad (53)$$

where the first square bracketed term corresponds to Home's share of the total world revenue and the second to the worldwide crop z risk premium which depends on its variance-mean ratio. When choosing its tax policy, Home has to consider the total domestic risk premium, which is approximated by

$$TRP \equiv (1 - b)[b/2 + q(1 - b)] \int_0^1 \alpha(z) \text{Var}[\tilde{y}_T^W(z)] / (2y_T^W(z)) dz.$$

The effect of an increase in the tax index is negative on the share of revenue, but since it is proportional to $(1 - b)^2$, it is relatively small when b is large. We will thus concentrate on the effects of the tax on the crops' worldwide risk premia.

Consider the case $\kappa = 0$. Each crop is produced by one country only and its variance-mean ratio, equal to $a(z)[1 - \psi(z)]$, does not depend on its relative surface: because both the variance and the mean of crop z increase with $B(z)$, their scale effects cancel each other. However, the tax policy has a negative impact on the survival probability $\psi(z)$ and thus increases the worldwide risk premium of the crop. As a consequence, if b is large, risk aversion leads to a smaller tax index than the one under risk neutrality.⁴³ When $\kappa > 0$, some goods are produced by both countries and the effect of the domestic tax on their

⁴²Indeed, absent cross-externality effects ($\kappa = 0$), trade does not allow diversification of production risks because each crop is produced by one country only, but because Cobb-Douglas preferences lead to spending equal to a constant share of the revenue for each crop, producers' total revenue is certain if the total domestic revenue is certain: the idiosyncratic profit risks of farmers are completely diversifiable at the country level and the domestic revenue is indeed non-stochastic (recall that industrial production is certain by assumption). When $\kappa > 0$, some crops are produced by both countries. The corresponding amounts are shared by Home and Foreign producers and their idiosyncratic profit risks are completely diversifiable worldwide.

⁴³This is also the case under autarky.

global risk premium is less straightforward. We have

$$\text{Var}[\tilde{y}_T^W(z)]/y_T^W(z) = s(z)a(z)[1 - \psi(z)] + [1 - s(z)]a^*(z)[1 - \psi^*(z)]$$

where $s(z) = y_T(z)/y_T^W(z)$ is Home's share of the expected world production. In addition to the direct effect of the tax on the mean-variance ratio, there is also a negative effect on Home's share of crop z production, which may have a positive or negative impact on the worldwide crop risk premium depending on the difference in the mean-variance ratios of the countries' productions. By decreasing its tax, Home increases its share and decreases the variance-mean ratio of its production. These two effects reduce the worldwide risk premium of crops with small domestic variance-mean ratios compared to those of Foreign, but they are countervailing otherwise.

7 Fertilizers

Our focus being on biodiversity effects in agricultural production, we have not discussed the impact of trade on the use of fertilizers. However, because they have considerable effects on both crop yields and on the environment (and human health), changes in the openness of countries to trade are likely to impact the way their use is regulated.⁴⁴ We may thus expect that food price behavior is also affected through this channel. It is possible to analyze these changes 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:

⁴⁴Commercial fertilizers are responsible for 30% to 50% of crop yields (Stewart et al., 2005). Sutton et al. (2011a,b) find that half of the nitrogen added to farm fields ends up polluting water or air. Excess of nitrogen and phosphorus in freshwater increases cancer risk and creates aquatic and marine dead zones through eutrophication. In the air, nitrates contribute to ozone generation which causes respiratory and cardiovascular diseases. Sutton et al. (2011a) estimates that in the European Union the benefits of nitrogen for agriculture through the increase in yields amount to €25 billion to €130 billion per year and that they cause between €70 billion and €320 billion per year in damage.

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.

8 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, 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 policies 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.

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Appendix

A Proof of Proposition 1

For given t, t^*, c, c^* , (16) and (17) define a system of two linear equations with two unknowns. Solving this system gives (20). 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 (21) 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. (18) and (19) 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

Differentiating (32) where $q = \xi^{-1}(t^*/t)$ with respect to t yields

$$\frac{\partial W_0}{\partial t} = -\frac{R'(q)}{R(q)} \frac{\xi(q)}{t \xi'(q)} - (1-b) \frac{q}{t} + \frac{Nh}{t \sqrt{2 \ln t}}.$$

Equalizing to 0 and rearranging terms gives (33). Using $\sqrt{2 \ln t} = \tau/c$, $c = 2q c_A$ and $\tau_A/c_A = Nh/(1-b)$ gives (34).

(ii) & (iv). With $A(z) = A_0[z/(1-z)]^{1/\theta}$, we have $\xi(z) = A(z)z/(1-z) = A_0[z/(1-z)]^{(1+\theta)/\theta}$, hence $\xi(q)/\xi'(q) = q(1-q)\theta/(1+\theta)$. Using (15) and $\sqrt{2 \ln t_A} = Nh/(1-b)$, we arrive at $\partial W_0/\partial t = (1-b)f(t, q)/t$ where

$$f(t, q) \equiv \sqrt{\frac{\ln t_A}{\ln t}} - \frac{2q(1-q)}{b + 2q(1-b)} \frac{\theta}{1+\theta} - q. \quad (54)$$

Home's and Foreign's BRs are implicitly defined by t that solves $f(t, \xi^{-1}(t^*/t)) = 0$ for given $t^* \geq 1$, and t^* that solves $f(t^*, 1 - \xi^{-1}(t^*/t)) = 0$ for given $t \geq 1$ respectively,

provided that the second-order conditions are satisfied. Using $f(t, q)|_{t=BR(t^*)} = 0$, we get

$$\frac{\partial^2 W_0}{\partial t^2} = \frac{1-b}{t} \left(\frac{\partial f(t, q)}{\partial t} + \frac{\partial f(t, q)}{\partial q} \frac{dq}{dt} \right)$$

where

$$\frac{dq}{dt} = \frac{-t^*}{t^2 \xi'(q)} = \frac{-\xi(q)}{t \xi'(q)} = -\frac{\theta q(1-q)}{t(1+\theta)}$$

and

$$\frac{\partial f(t, q)}{\partial t} = -\frac{1}{2t \ln t} \sqrt{\frac{\ln t_A}{\ln t}} = -\frac{1}{t} \left(\frac{2(1-q)q}{b+2q(1-b)} \frac{\theta}{1+\theta} + q \right)^3 \left(\frac{1-b}{Nh} \right)^2$$

where we have used (54) to substitute $\ln t$ by its expression solving $f(t, q) = 0$. We thus have

$$\frac{\partial^2 W_0}{\partial t^2} = -\frac{1-b}{t^2} \left[\left(\frac{2(1-q)q}{b+2q(1-b)} \frac{\theta}{1+\theta} + q \right)^3 \left(\frac{1-b}{Nh} \right)^2 + \frac{\theta q(1-q)}{1+\theta} \frac{\partial f(t, q)}{\partial q} \right]$$

where

$$\frac{\partial f(t, q)}{\partial q} = \frac{[\theta - (1+\theta)(1-b)][q(1-b) + b]4q - b[2\theta + b(1+\theta)]}{(1+\theta)[b+2q(1-b)]^2}.$$

As $\theta \geq 1$ and $b > 1/2$, we have $\theta/(1+\theta) > 1-b$ and $\partial f(t, q)/\partial q$ has the same sign as

$$q^2(1-b) + bq - \frac{b[b/2 + \theta/(1+\theta)]}{2[\theta/(1+\theta) - (1-b)]}.$$

The associated quadratic equation has a negative and a positive root, the latter being given by

$$q_s = \frac{b}{2(1-b)} \left[\sqrt{1 + \frac{1-b}{b} \frac{b+2\theta/(1+\theta)}{\theta/(1+\theta) - (1-b)}} - 1 \right]. \quad (55)$$

$\partial f(t, q)/\partial q$ is increasing over $[0, 1]$ with $\partial f(t, q)/\partial q < 0$ iff $q < q_s$. Consequently, $\partial^2 W_0/\partial t^2 < 0$ for all $q > q_s$, and for $q < q_s$, the condition for $\partial^2 W_0/\partial t^2 \leq 0$ is given by

$$q^2 \left(\frac{2(1-q)}{b+2q(1-b)} \frac{\theta}{1+\theta} + 1 \right)^3 \left(\frac{1-b}{Nh} \right)^2 + \frac{\theta(1-q)}{1+\theta} \frac{\partial f(t, q)}{\partial q} \geq 0. \quad (56)$$

Since $\partial f(t, q_s)/\partial q = 0$ and $\partial f(t, q)/\partial q < 0$ when $q < q_s$, the LHT is positive for $q = q_s$ but negative for $q = 0$. By continuity, there exists $\underline{q} \in (0, q_s)$ that satisfies this condition as an equality, and we have $\partial^2 W_0/\partial t^2 < 0$ for all $q > \underline{q}$. We have $\underline{q} < 1/2$ if

$$\frac{1}{4} \left(\frac{\theta}{1+\theta} + 1 \right)^3 \left(\frac{1-b}{Nh} \right)^2 + \frac{1}{2} \frac{\theta}{1+\theta} \frac{\partial f(t, 1/2)}{\partial q} > 0$$

where $\partial f(t, 1/2)/\partial q = -(1 + b\theta)/(1 + \theta)$, which gives

$$\frac{(1 + 2\theta)^3}{2\theta(1 + \theta)(1 + b\theta)} > \left(\frac{Nh}{1 - b}\right)^2.$$

The derivative of the LHS wrt θ is given by

$$\frac{1}{2} \left(\frac{1 + 2\theta}{\theta(1 + \theta)(1 + b\theta)} \right)^2 [\theta^2(2 - b) + 2\theta(1 - b) - 1]$$

which is positive for $\theta > 1$. As the LHS tends to $4/b$ when θ is large, we have $\underline{q} < 1/2$ for all θ when $Nh < 2(1 - b)/\sqrt{b}$, which completes (ii). (iv) comes from the fact that (55) and (56) are independent of A_0 .

(i). Using

$$\frac{dq}{dt^*} = \frac{1}{t\xi'(q)} = \frac{\xi(q)}{t^*\xi'(q)} = \frac{\theta q(1 - q)}{t^*(1 + \theta)}$$

we get

$$\frac{\partial^2 W_0}{\partial t \partial t^*} = \frac{1 - b}{t} \frac{\partial f(t, q)}{\partial q} \frac{dq}{dt^*} = \frac{1 - b}{tt^*} \frac{\partial f(t, q)}{\partial q} \frac{\theta q(1 - q)}{1 + \theta},$$

and thus $\partial^2 W_0/(\partial t \partial t^*) \leq 0$ iff $\partial f(t, q)/\partial q \leq 0$. Hence, environmental tax indexes are strategic substitutes ($BR'(t^*) < 0$) for q lower than $q_s > 1/2$ since $\partial f(t, 1/2)/\partial q = -(1 + b\theta)/(1 + \theta) < 0$. Similarly, we have $\partial W_0^*/\partial t^* = (1 - b)f(t^*, q^*)/t^*$ and

$$\frac{\partial^2 W_0^*}{\partial t \partial t^*} = \frac{1 - b}{t^*} \frac{\partial f(t^*, q^*)}{\partial q^*} \frac{dq^*}{dt} = -\frac{1 - b}{t^*} \frac{\partial f(t^*, q^*)}{\partial q^*} \frac{dq}{dt}$$

where

$$\frac{dq}{dt} = \frac{-t^*}{t^2 \xi'(q)} = \frac{-\xi(q)}{t \xi'(q)} = -\frac{\theta q(1 - q)}{t(1 + \theta)}$$

which gives

$$\frac{\partial^2 W_0^*}{\partial t \partial t^*} = \frac{1 - b}{tt^*} \frac{\partial f(t^*, q^*)}{\partial q^*} \frac{\theta q(1 - q)}{1 + \theta}.$$

Consequently, $BR^*(t) < 0$ iff q^* is larger than q_s , hence q lower than $1 - q_s$.

(iii). We can compare $BR'(t^*)$ to $1/BR^*(BR(t^*))$ using

$$\frac{\partial^2 W_0}{\partial t^2} = -\frac{1 - b}{t^2} \frac{\theta q(1 - q)}{1 + \theta} \frac{\partial f(t, q)}{\partial q} (1 - \Upsilon(q))$$

where

$$\Upsilon(q) \equiv -\frac{(1 + \theta) \left(\frac{2(1 - q)q}{b + 2q(1 - b)} \frac{\theta}{1 + \theta} + q \right)^3}{(1 - q)q\theta \partial f(t, q)/\partial q} \left(\frac{1 - b}{Nh} \right)^2.$$

We have

$$BR'(t^*) = -\frac{\partial^2 W_0}{\partial t \partial t^*} \bigg/ \frac{\partial^2 W_0}{\partial t^2} = \frac{1}{\xi(q)(1 - \Upsilon(q))}$$

and

$$BR^{*'}(t) = - \frac{\partial^2 W_0^*}{\partial t \partial t^*} / \frac{\partial^2 W_0^*}{\partial t^{*2}} = \frac{\xi(q)}{1 - \Upsilon(1 - q)}.$$

Wherever $BR'(t^*) < 0$ (which implies $\Upsilon(q) > 1$) we have $BR'(t^*) > 1/BR^{*'}(t)$ iff $1 < (1 - \Upsilon(q))(1 - \Upsilon(1 - q))$. At $q = 1/2$, we have

$$\Upsilon(1/2) = \frac{(1 + 2\theta)^3}{4\theta(1 + \theta)(1 + b\theta)} \left(\frac{1 - b}{Nh} \right)^2$$

and the condition becomes $1 < (1 - \Upsilon(1/2))^2$, hence $\Upsilon(1/2) > 2$, which gives

$$\frac{(1 + 2\theta)^3}{8\theta(1 + \theta)(1 + b\theta)} > \left(\frac{Nh}{1 - b} \right)^2.$$

As the LHS tends to $1/b$ when θ is large, we have $BR'(t^*)|_{q=1/2} > -1/A_0 > 1/BR^{*'}(t)|_{q=1/2}$ for all θ when $Nh < (1 - b)/\sqrt{b}$.

C Proof of Proposition 4

As we have to characterize the solutions of quadratic equations in the following, consider the roots of $\sum_{i=0}^{i=2} \nu_i q^i = 0$ where $\nu_2 > 0, \nu_0 > 0, \nu_1^2 > 4\nu_2\nu_0$, that we denote by $q_1 \equiv -(\sqrt{\nu_1^2 - 4\nu_2\nu_0} + \nu_1)/2\nu_2$ and $q_2 \equiv (\sqrt{\nu_1^2 - 4\nu_2\nu_0} - \nu_1)/2\nu_2$. We have $q_2 < 1$ if $\sqrt{\nu_1^2 - 4\nu_2\nu_0} < 2\nu_2 + \nu_1$, which implies $\nu_1 + 2\nu_2 > 0$ in which case $q_2 < 1$ iff $\nu_1^2 - 4\nu_2\nu_0 < (2\nu_2 + \nu_1)^2 = 4\nu_2^2 + \nu_1^2 + 4\nu_2\nu_1$ which simplifies to $\sum_{i=0}^{i=2} \nu_i > 0$. We have $q_1 > 0$ iff $\sqrt{\nu_1^2 - 4\nu_2\nu_0} < -\nu_1$ which is impossible when $\nu_1 > 0$. If $\nu_1 < 0$, q_1 is strictly positive and it is lower than 1 iff $\sqrt{\nu_1^2 - 4\nu_2\nu_0} > -(2\nu_2 + \nu_1)$ which is always satisfied if $0 > \nu_1 > -2\nu_2$. In the case $\nu_1 < -2\nu_2$, $q_1 < 1$ iff $\sum_{i=0}^{i=2} \nu_i < 0$.

(i). Using (54) and denoting $x(t) = \sqrt{\ln t_A / \ln t}$, the equation $f(t, q) = 0$ can be rewritten as

$$[\theta/(1 + \theta) - 1 + b] q^2 + [(1 - b)x(t) - b/2 - \theta/(1 + \theta)] q + x(t)b/2 = 0 \quad (57)$$

where $\theta/(1 + \theta) > 1 - b$ since $\theta \geq 1$ and $b > 1/2$. The sum corresponding to $2\nu_2 + \nu_1$ is given by $\theta/(1 + \theta) - (1 - b)(2 - x(t)) - b/2$ which is positive if $x(t) > 2 - (\theta/(1 + \theta) - b/2)/(1 - b)$ hence $t < t_A^{-[2 - \frac{1}{1-b}(\frac{\theta}{1+\theta} - \frac{b}{2})]^2} \leq 1$. As $t \geq 1$, we cannot have $q_2 < 1$ which rules out this root. The condition $\nu_1 < 0$ corresponds to $t > t_A^{-[b/2 + \theta/(1 + \theta)]^2/(1 - b)^2}$ which is lower than 1, and the sum of the coefficients of (57) is equal to $(1 - b/2)[x(t) - 1]$ which is negative iff $x(t) \leq 1$ hence $t \geq t_A$. Consequently, we have $1 \geq q_1 > 0$ provided that $t \geq t_A$. This solution exists if the discriminant of (57), given by

$$\Delta_q \equiv [(1 - b)x(t) - b/2 - \theta/(1 + \theta)]^2 - 2bx(t)[\theta/(1 + \theta) - 1 + b],$$

is positive, a condition that can be written as

$$(1-b)^2 x(t)^2 - [2\theta/(1+\theta) - b(1-b)] x(t) + [b/2 + \theta/(1+\theta)]^2 \geq 0.$$

The corresponding discriminant,

$$\Delta_x \equiv [2\theta/(1+\theta) - b(1-b)]^2 - 4(1-b)^2 [b/2 + \theta/(1+\theta)]^2 = 4b(2-b) [\theta/(1+\theta) - 1+b] \theta/(1+\theta)$$

is positive, and we must have either $x(t) \leq x_1$ or $x(t) \geq x_2$ where

$$x_i = \frac{1}{2(1-b)^2} \left[2\theta/(1+\theta) - b(1-b) + (-1)^i \sqrt{\Delta_x} \right].$$

The sum of the coefficients of Δ_q is equal to $[b/2 + \theta/(1+\theta) - 1]^2 > 0$, and the sum $2\nu_2 + \nu_1$ gives $(1-b)(2-b) - 2\theta(1+\theta) < 0$ since $\theta/(1+\theta) > 1-b > (1-b)(1-b/2)$. We thus have $x_2 > x_1 > 1$ and two possibilities: either $t \leq t_A^{-x_2} < 1$ or $t \geq t_A^{-x_1}$. As $t \geq 1$, the latter guarantees that $x(t) < x_1$, and thus that q is given by the smallest root of (57), which can be written as $q = S(x(t))$ where

$$S(x) \equiv \frac{1}{2} \left[\varpi (\varpi_0 - (1-b)x) - \sqrt{\varpi^2 (\varpi_0 - (1-b)x)^2 - 2b\varpi x} \right] \quad (58)$$

with $\varpi_0 = [b/2 + \theta/(1+\theta)]$ and $\varpi = [\theta/(1+\theta) - 1+b]^{-1}$. We have $S(0) = 0$, $S(1) = 1$,

$$\begin{aligned} S'(x) &= \frac{1}{2} \left[-(1-b)\varpi - \frac{-(1-b)\varpi^2 (\varpi_0 - (1-b)x) - b\varpi}{\sqrt{\varpi^2 (\varpi_0 - (1-b)x)^2 - 2b\varpi x}} \right] \\ &= \frac{\varpi b + 2S(x)(1-b)\varpi}{2[\varpi (\varpi_0 - (1-b)x) - 2S(x)]} > 0, \end{aligned} \quad (59)$$

and, differentiating the log of this expression,

$$\frac{S''(x)}{S'(x)} = \frac{2S'(x)(1-b)\varpi}{\varpi b + 2S(x)(1-b)\varpi} + \frac{\varpi(1-b)x + 2S'(x)}{\varpi (\varpi_0 - (1-b)x) - 2S(x)} > 0,$$

hence $S''(x) > 0$. As $x(t)$ verifies

$$x'(t) = -\frac{\sqrt{\ln t_A}}{2t \ln t \sqrt{\ln t}} = -\frac{x}{2t \ln t} < 0, x''(t) = -\frac{x'(t)t \ln t - x[\ln t + 1]}{2(t \ln t)^2} = x \frac{\ln t + 3/2}{2(t \ln t)^2} > 0$$

we have $q = Q(t) \equiv S(x(t))$ with $Q'(t) = S'(x(t))x'(t) < 0$ and $Q''(t) = S''(x(t))x'(t)^2 + S'(x(t))x''(t) > 0$. Symetrically, we have for Foreign that $q^* = Q(t^*) \equiv S(\sqrt{\ln t_A / \ln t^*})$.

(ii) & (iii). Suppose that t_N^* corresponds to Foreign's equilibrium strategy (same reasoning applies if we suppose that Home as a given equilibrium strategy t_N). The

first equation of (37) can be written as $Q(t) = 1 - Q(t_N^*)$ where the RHS is a constant for given t_N^* . As $Q(\cdot)$ is decreasing, there is at most one t that solves this equation, which thereby must correspond to Home's equilibrium strategy: we have $t_N = T(t_N^*) \equiv Q^{-1}(1 - Q(t_N^*))$. The second equation defines the pair (t_N, t_N^*) that corresponds to a given A_0 , hence $(t_N(A_0), t_N^*(A_0))$. Considering small changes in A_0 and using the implicit equation theorem, we obtain $T'(t_N^*) = -Q(t_N^*)/Q'(t_N) < 0$ and $T''(t_N^*) = -[Q''(t_N^*) + Q''(t_N)T'(t_N^*)^2]/Q'(t_N) > 0$. Hence, the set of Nash equilibria corresponding to the possible values of A_0 can be depicted as a decreasing and convex curve in the (t, t^*) plane. Differentiating the log of the second equation using $t_N = T(t_N^*)$, we get

$$\frac{dt_N^*}{dA_0} = \frac{1}{A_0} \left(\frac{1}{t_N^*} - \frac{T'(t_N^*)}{T(t_N^*)} - \frac{1+\theta}{\theta} \left(\frac{Q'(t_N)T'(t_N^*)}{Q(t_N)} - \frac{Q'(t_N^*)}{Q(t_N^*)} \right) \right)^{-1}.$$

In particular, for $A_0 = 1$, using $t_N^*(1) = t_N(1)$, we have $Q(t_N) = 1/2, T'(t_N^*) = -1$ and

$$\left. \frac{dt_N^*}{dA_0} \right|_{A_0=1} = \left(\frac{2}{t_N(1)} + \frac{1+\theta}{\theta} 4Q'(t_N(1)) \right)^{-1}$$

where $Q'(t) = S'(x(t))x'(t)$ with

$$x'(t) = -\frac{x(t)}{2t \ln t} = -\frac{q^3}{2t \ln t_A} \left(\frac{2(1-q)}{b+2q(1-b)} \frac{\theta}{1+\theta} + 1 \right)^3,$$

and

$$x(t) = \frac{2q(1-q)}{b+2q(1-b)} \frac{\theta}{1+\theta} + q.$$

We thus get, using (59),

$$x(t_N(1)) = \frac{1+2\theta}{2(1+\theta)}, S'(x(t_N(1))) = \frac{1+\theta}{1+b\theta}, x'(t_N(1)) = -\frac{1}{16t \ln t_A} \left(\frac{1+2\theta}{1+\theta} \right)^3,$$

which gives

$$Q'(t_N(1)) = -\frac{1}{16t \ln t_A} \left(\frac{1+2\theta}{1+\theta} \right)^3 \frac{1+\theta}{1+b\theta}$$

hence

$$\left. \frac{dt_N^*}{dA_0} \right|_{A_0=1} = \left(\frac{2}{t_N} - \frac{(1+2\theta)^3}{4t_N \ln t_A \theta (1+\theta)(1+\theta b)} \right)^{-1} = \frac{t_N(1)}{2 - \Upsilon(1/2)} < 0.$$

D Proof of Proposition 5

At a symmetric equilibrium, as $\hat{R}(1/2) = 2(1 - b)$, $\xi(1/2) = 1$, $\xi'(1/2) = A'(1/2) + 4$, and thus $\varepsilon(1/2) = 2/[A'(1/2) + 4]$, (34) simplifies to

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

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

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

E Proof of Proposition 6

Differentiating (29) with respect to t , we obtain

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

At a symmetric equilibrium, using (38) to obtain $(A(z) - 1)/(A(z) + 1) = 2(z - 1/2)/\theta$ and integrating gives (42). Using (41) in (42) and collecting terms, we arrive at

$$\left. \frac{\partial W_\kappa}{\partial t} \right|_{t=t^*} = \frac{Nh}{t\sqrt{2 \ln t}} - (1 - b) \left[\frac{1}{2t} + \kappa \frac{2(1 + t\kappa)^2 - \theta t\kappa}{2(1 + 2t\kappa)(1 + t\kappa)^2} \right].$$

Denote by t_0 the optimal tax when there is no cross-externality effects, i.e. $\kappa = 0$. It verifies (31) where $q = 1/2$. We have

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

which is positive if

$$\theta \geq \frac{2(1 + t_0\kappa)^2}{t_0\kappa} \geq 8.$$

At a symmetric equilibrium, we have $t_N = BR(t_N)$. As $(\partial W_\kappa / \partial t)|_{t=t_0} < 0$ when θ is small enough (and always if it is lower than 8), we have $BR(t_0) < t_0$ assuming W_κ is concave in t which is the case when κ is small since W_0 is concave. Also, at least for κ small, we have $BR'(t) < 0$ implying $t_N = BR(t_N) < t_0$.

Likewise, we have

$$\begin{aligned} \frac{1}{1-b} \frac{\partial W_\kappa}{\partial t} \Big|_{t=t^*=t_A} &= \frac{1}{2t_A} + \frac{\kappa}{1+t_A\kappa} - \kappa \frac{2(1+t_A\kappa)^2 - \theta t_A\kappa}{2(1+2t_A\kappa)(1+t_A\kappa)^2} \\ &= \frac{1}{2t_A} + \frac{t_A\kappa^2}{1+t_A\kappa} \frac{2(1+t_A\kappa) + \theta}{2(1+2t_A\kappa)(1+t_A\kappa)} > 0 \end{aligned} \quad (60)$$

hence, at least for κ small, $BR(t_A) > t_A$ with $BR'(t) < 0$ implying $t_N = BR(t_N) > t_A$.

F Proof of Proposition 7

At a symmetric equilibrium, (43) simplifies to

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

where $\bar{z} + \underline{z} = 1$, hence $(\partial W_\kappa / \partial q)|_{t=t^*} = 2(1-b)$. We also obtain using (30) that at a symmetric equilibrium

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

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

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

and

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

yields (44). Differentiating, we get

$$\frac{dq^2}{dt d\kappa} \Big|_{t=t^*} = -\theta \frac{(4\theta - 1)(1+t\kappa)^2 + 4(1+t\kappa) + 2\theta}{12(1+t\kappa)^2[(1+t\kappa) + \theta]^2} < 0.$$

Assuming $\theta \leq 8$, we thus get $(dW_\kappa/dq)|_{t=t^*=t_0} < 0$. Using (60) we obtain

$$\frac{1}{1-b} \frac{dW_\kappa}{dt} \Big|_{t=t^*=t_A} = \frac{1}{2t_A} + \frac{t_A\kappa^2[2(1+t_A\kappa) + \theta]}{2(1+2t_A\kappa)(1+t_A\kappa)^2} - \frac{3 + 9t_A\kappa + 4(t_A\kappa)^2}{6t_A(1+t_A\kappa)[1+t_A\kappa + \theta]}$$

which increases with θ . As $\theta \geq 1$, we have (denoting $k = t_A \kappa$),

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

hence, at least for κ small, $BR(t_A) > t_A$ with $BR'(t) < 0$ implying $t_N = BR(t_N) > t_A$.

G Proof of Proposition 8

Without biodiversity effects, using (45) and (46) with $\kappa = 0$, we obtain that $v(\tilde{y}_A^W(z)) \geq v(\tilde{y}^W(z))$ iff

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

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 (47) and assuming that $t \geq t_A$, we obtain that $v(\tilde{y}_A^W(z)) \geq v(\tilde{y}^W(z))$ iff

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

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 (45), we have $v(\tilde{y}_A^W(z)) \geq v(\tilde{y}^W(z))$ iff

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

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.

H Proof of Proposition 9

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 (51). Similar derivations for $p_d^\gamma(z) = E[\tilde{p}(z)] - s_d^\gamma \sigma(\tilde{p}(z))$ yield (50) and (52).

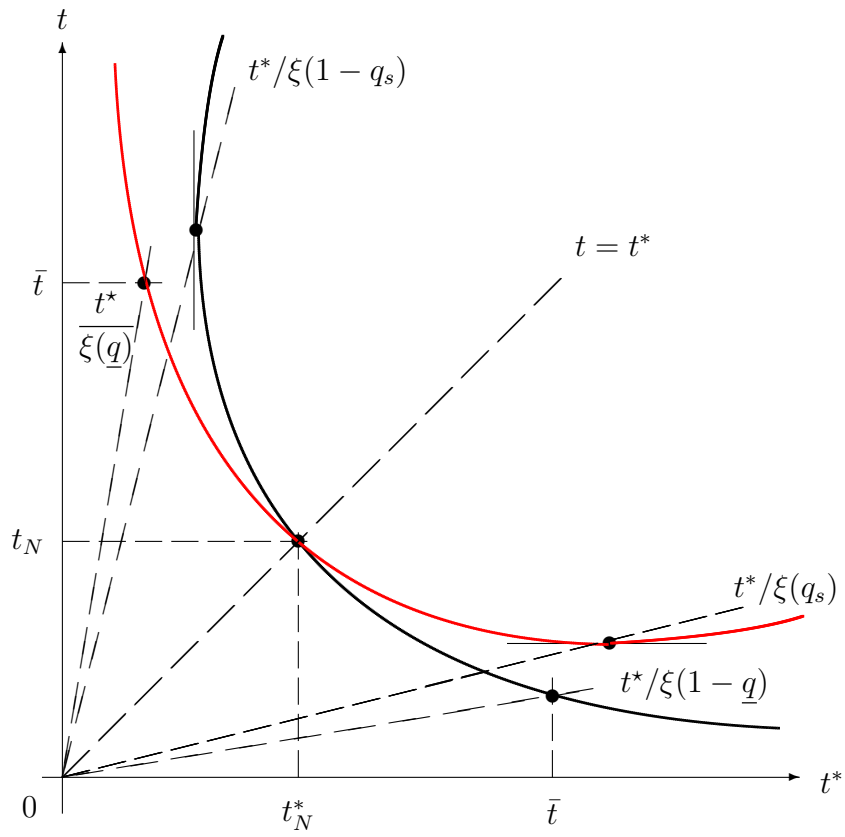


Figure 1: Best Responses and Nash equilibrium, symmetric case ($A_0 = 1$).

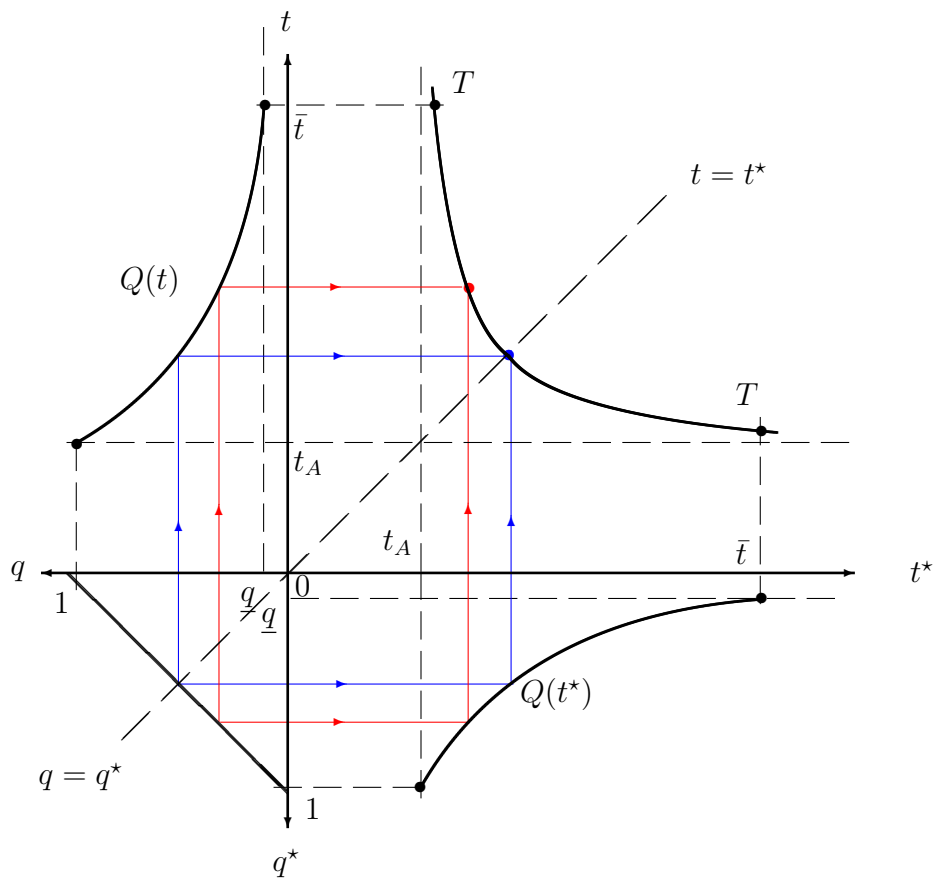


Figure 2: Nash equilibrium and comparative advantages.

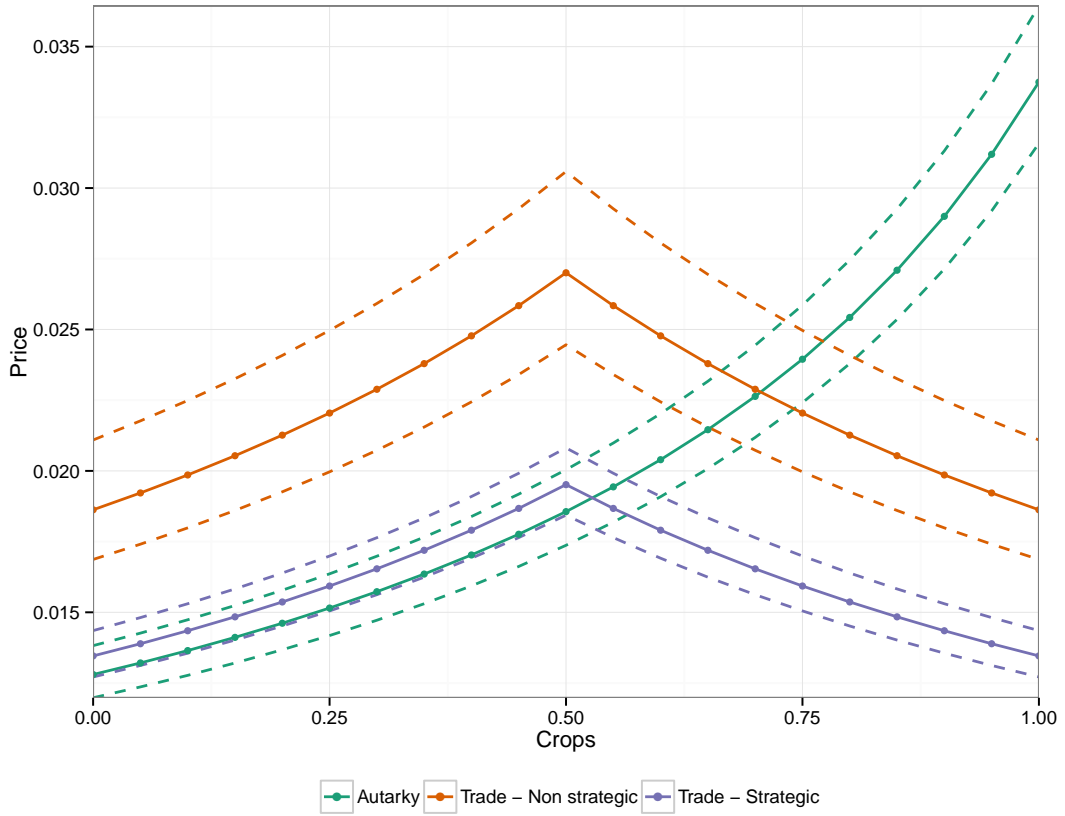


Figure 3: Average prices and price volatility (confidence interval at 95% confidence level) without biodiversity effects. $\kappa = 0$, $N=100$, $h = 10^{-3}$, $b = 0.8$, $\ell = 20$, $\theta = 2.22$, $\mu = 1$, $a(1/2) = 29$.

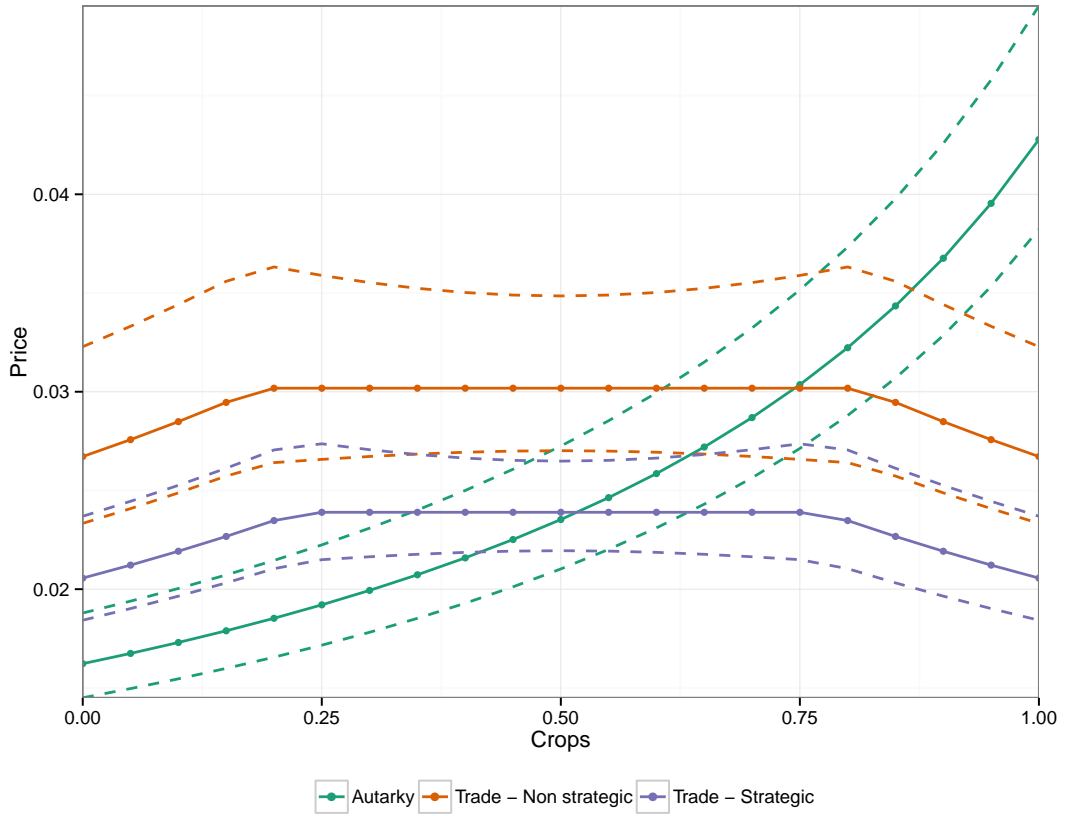


Figure 4: Average prices and price volatility (confidence interval at 95% confidence level) with biodiversity effects. $\kappa = 0.3$, $N=100$, $h = 10^{-3}$, $b = 0.8$, $\ell = 20$, $\theta = 2.22$, $\mu = 1$, $a(1/2) = 29$.

Table 1: Decomposition of welfare variations

Value of κ	$\tau^* = 0$		$\tau^* = \tau_A^*$		Nash equilibrium	
	0.08	0.16	0.08	0.16	0.08	0.16
Non strategic – percentage changes relative to autarky						
Tax (τ/c)	359.76	340.53	345.87	328.13	337.95	320.07
Revenue effect	-69.99	-70.58	-69.34	-69.98	-68.96	-69.58
Price effect	-29.15	-35.29	-30.96	-37.09	-32.04	-38.31
Environmental effect	7.86	7.03	7.56	6.77	7.38	6.60
Total welfare (W_κ)	-100.37	-106.75	-102.83	-109.21	-104.31	-110.86
$\bar{z} - \underline{z}$ (% of crops)	52.95	78.04	53.15	78.25	53.27	78.40
Strategic – percentage changes relative to autarky						
Tax (τ/c)	74.00	77.67	72.33	75.99	73.03	76.76
Revenue effect	-68.81	-69.58	-68.24	-69.03	-68.48	-69.26
Price effect	-27.69	-34.04	-29.55	-35.89	-28.78	-35.10
Environmental effect	1.62	1.60	1.58	1.57	1.60	1.58
Total welfare (W_κ)	-98.10	-104.87	-100.67	-107.41	-99.60	-106.33
$\bar{z} - \underline{z}$ (% of crops)	52.09	77.52	52.35	77.77	52.24	77.66

All numbers correspond to percentage changes relative to autarky except for the fraction of crops produced by both countries ($\bar{z} - \underline{z}$). *Parameter values:* $\theta = 8.11$, $T^* = 6.2$, $T = 10$, $b^* = b = 0.855$, $N = 1$, $N^* = 3$, $\ell = 62$, $\ell^* = 8$, $h = 0.01$, $\rho = 3$, $\rho^* = 6$.