Trade policy coordination and food price volatility

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Paper prepared for presentation at the EAAE 2014 Congress
'Agri-Food and Rural Innovations for Healthier Societies'

August 26 to 29, 2014
Ljubljana, Slovenia

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June 30, 2014

Abstract

Many countries adjust their trade policies countercyclically to food prices, to such extent that the use of export restrictions by numerous food exporters has occasionally threatened the food security of food importing countries. These trade policies are not consistent with the terms-of-trade motivation often retained to characterize the payoff frontier of self-enforcing trade agreements, as these policies can worsen the country's terms of trade. This paper analyzes trade policy coordination when trade policies are driven by terms-of-trade effects and a desire to reduce domestic food price volatility. This framework implies that importing and exporting countries have incentives to deviate from cooperation at different periods: exporter when prices are high and importers when prices are low. Since staple food prices tend to have positively-skewed distributions, with more prices below mean than above but with occasional spikes, a self-enforcing agreement generates asymmetric outcomes. Although an importing country suffers less in the trade war than an exporting country, this latter has larger incentives to deviate from a cooperative trade policy because positive deviations from mean price are larger than negative ones. Thus, because of the asymmetry of the distribution of commodity prices, it may be more difficult to discipline exports taxes than tariffs in trade agreements.

Keywords: commodity price stabilization, export restrictions, repeated game, WTO.

JEL classification: F13, Q17, Q18.

*The author thanks Jean-Marc Bourgeon, Quy-Toan Do, Sébastien Jean and Will Martin for helpful comments. This research was generously supported by the Knowledge for Change Program (KCP), and by the European Union's Seventh Framework Programme FP7/2007–2011 under Grant Agreements no 290693 FOODSECURE. The author only is responsible for any omissions or deficiencies. The European Union and European Commission are not accountable for the content of the paper.

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1 Introduction

During food price spikes, food exporting countries frequently use export restrictions to insulate their domestic markets from the high prices on world market. Their use can be so widespread that the high levels reached by international prices could also be seen as a consequence of these interventions,[1] and the restrictions can be so stringent that they may lead to a near disappearance of the world market as happened to the rice market for nine months in 1973 (Timmer, 2010). Food importing countries do not stay inactive, either: to protect their consumers, they decrease their tariffs. When world prices are low, the situation reverses: importers raise their import duty. In summary, on food markets countries routinely adjust their trade barriers to insulate domestic markets from international price variability (Anderson and Nelgen, 2012). The lack of commitment to leave the borders open may decrease trust in the world trade system and lead to costly policies. Importing countries expecting food exporters to restrict their exports in times of scarcity will move away from a specialization consistent with their comparative advantages to ensure a higher self-sufficiency or will carry expensive public stocks. For example, the current large-scale public interventions in Asian countries, through which many countries attempt to achieve self-sufficiency in major staples, can be largely explained by their experience of the 1972/73 food crisis and their heavy dependence until the 1970s on a foreign aid that was not free of political considerations (Rothschild, 1976, Rashid et al., 2008).

The widespread use of export restrictions in the 2007/08 food prices spike[2] and the Russian export ban in 2010 after a devastating drought spurred call for WTO disciplines on export restrictions (FAO et al., 2011, HLPE, 2011). Such proposals were coldly met by several food-exporting developing countries (Mitra and Josling, 2009) and were not considered in the agreement reached at the WTO 9th Ministerial Conference at Bali (WTO, 2013).[3] So far according to agricultural draft modalities, in case of another agreement there would not be any significant strengthening of disciplines on export restrictions (WTO, 2008). Given the importance of export restrictions in influencing trust in world markets and so food policies in the long run, it is essential to understand what prevents a trade agreement on this issue. This paper contributes to the understanding of what trade agreements would be acceptable with respect to trade policies that are countercyclical to food prices. Using some concepts of game theory, it explores the possibility of cooperation through a self-enforcing trade agreement between countries that, on their own, would try to decrease the volatility of their domestic food price using trade policies.

Although the main purpose of trade agreements is to liberalize trade, it has been shown that they also reduce the volatility of trade policy (Mansfield and Reinhardt, 2008, Cadot et al., 2010). A formal treatment of countercyclical trade policies and of the extent to which self-enforcing agreements can discipline countercyclical trade policies has been proposed in Bagwell and Staiger (1990, 2003). These papers show that the threat to go back to a non-cooperative situation is sufficient to support a tacit cooperation when countries enter into repeated interactions. However, this cooperation is not necessarily synonymous with free trade, because when trade shocks are large enough the incentive to deviate from cooperation would be too high in free trade. These papers focus on trade policies motivated by terms-of-trade gains and explain the changes in trade policies by the changes in potential terms-of-trade gains

[1]This is the dominant interpretation of the 2007/08 price spikes on the rice market (Slayton, 2009).

[2]In a survey of country responses to the food security crisis, Demeke et al. (2009) show that 25 developing and emerging countries in a panel of 81 restricted or banned exports.

[3]This was not a new issue as proposals to regulate export restrictions were rejected by many member countries at the beginning of the Doha Round negotiations (WTO, 2004).

arising from idiosyncratic supply shocks. For food products, terms-of-trade theory may not be sufficient to explain the behavior of trade barriers. Examples of deviations from this theory are the export bans used by many countries during the recent food crisis that precludes any gain from trade, and the export subsidies used by wealthy countries in periods of low prices, which deteriorate the terms-of-trade of the countries using them. More generally according to Bagwell and Staiger (1990), terms-of-trade motivated policies are function of the trade volumes, which characterize the potential gains from manipulating terms-of-trade and which arises from idiosyncratic shocks. However, as shown in Anderson and Nelgen (2012, Table 1) protection in food products is negatively correlated with deviations from trend in their international price. So to account for the extent of trade policy adjustments in food products and to characterize the payoff frontier of self-enforcing trade agreements, we need a model in which governments are not just motivated by terms-of-trade gains, but want also to stabilize domestic prices.

Our starting point is the two-country partial equilibrium model of Bagwell and Staiger (1990). Two features distinguish our model from Bagwell and Staiger's one. Firstly to determine trade policies, policy makers maximize a social welfare function that includes, in addition to the sum of surpluses, a price-stabilization objective introduced through a reduced-form political economy approach. Secondly, we introduce aggregate uncertainty, which is what matters for world price volatility, while the original model was only concerned with idiosyncratic risk. This model is used to characterize the static Nash equilibria and the nature of a self-enforcing agreement on time-varying trade policies. These two assumptions imply that in tacit cooperation equilibria importing and exporting countries have incentives to deviate from cooperation at different periods: exporter when prices are high and importers when prices are low.

In addition to contributing to the theoretical literature on self-enforcing trade agreements, this paper contributes to the policy discussions on export restrictions. Despite the potential usefulness of disciplines on export restrictions, a few papers have pointed out that they are unlikely to be achievable in the framework of the WTO. For Abbott (2012), this is because policy makers will not accept to give away their right to stabilize their markets. For Cardwell and Kerr (forthcoming), the dispute settlement system cannot enforce such disciplines because export restrictions are of short duration compared to the time taken to settle disputes and because complainant countries may not be in positions to retaliate owing to insufficient bilateral trade levels. In this paper, disciplines on export restrictions are also proved difficult to achieve. Since staple food prices tend to have positively-skewed distributions (Deaton and Laroque, 1992), with more prices below mean than above but with occasional spikes, a self-enforcing agreement generates asymmetric outcomes. Although an importing country suffers less in the trade war than an exporting country, this latter has larger incentives to deviate from a cooperative trade policy because positive deviations from mean price are larger than negative ones. Thus, because of the asymmetry of the distribution of commodity prices, it may be more difficult to discipline in trade agreements exports taxes than tariffs.

The remainder of the paper is organized as follows. Section 2 presents the model in free trade and the equilibrium under given trade policies. Section 3 characterizes the social welfare functions and solve for the static Nash equilibria resulting from each country social welfare maximization. The interior Nash equilibrium will be used subsequently as the credible punishments in the dynamic game. Section 4 characterizes analytically the tacit cooperative equilibrium and illustrates numerically the results under symmetric and asymmetric price distribution. Section 5 concludes.

2 Model setup

We consider a partial equilibrium model of a global cereal market. There are two countries, "home" and "foreign", with identical demand schedules. The foreign country will be indicated by the superscript *. Production is assumed to be inelastic and is represented by two stochastic shocks, ε and ε^*, drawn from known distribution functions. Production shocks are perfectly observable. They are such that in free trade home is always in a position to export to foreign, so we assume that $\varepsilon \geq \varepsilon^*$.

Demand is represented by an inverse demand function $D(P)$ assumes to be linear and identical in both countries $D(P) = a - bP$ and $D^*(P^*) = a - bP^*$. Domestic prices clear the markets: $\varepsilon = D(P) + V$ and $\varepsilon^* = D^*(P^*) - V$, where V refers to the volume of trade.

Countries can apply specific trade taxes: τ and τ^*. When trade takes place, domestic prices are defined by combining world price, P^w, with trade policies:

$$P = P^w + \tau \text{ and } P^* = P^w + \tau^*. \tag{1}$$

This definition implies that when home exports, a negative τ is an export tax; conversely, when foreign imports, a positive τ^* is an import tax.

By combining above equations, we can characterize the volume of trade:

$$V = \frac{\varepsilon - \varepsilon^*}{2} + \frac{b(\tau - \tau^*)}{2}. \tag{2}$$

From (2), we define the free-trade trade volume as $V^f = (\varepsilon - \varepsilon^*)/2$. Trade is strictly positive for

$$\tau - \tau^* > \frac{\varepsilon^* - \varepsilon}{b} \text{ or } \tau^* - \tau < \frac{2V^f}{b}. \tag{3}$$

When (3) holds, world price is given by

$$P^w = \frac{a - (\varepsilon + \varepsilon^*)/2}{b} - \frac{\tau + \tau^*}{2}. \tag{4}$$

In a situation of free-trade, the world price would be $P^f = a/b - (\varepsilon + \varepsilon^*)/(2b)$, so that an alternative expression for the world price is

$$P^w = P^f - \frac{\tau + \tau^*}{2}. \tag{5}$$

The state of the system is defined by the two supply shocks ε and ε^*. Another state-space definition that will prove more useful is the aggregate risk, $\varepsilon + \varepsilon^*$ and the difference in idiosyncratic risks, $\varepsilon - \varepsilon^*$, which can also be represented by, respectively, the free-trade world price, P^f, and the free-trade trade volume, V^f.

3 The static game

In this section, we characterize the Nash equilibria of the static game in which each country applies the trade taxes maximizing a social welfare function that accounts, in addition to usual measures of surplus, for policy-makers dislike of food price volatility. The resultant interior trade policies are costly for both countries and will serve as punishments in the repeated game.

3.1 Social welfare function

Governments tend to offset international price variations by adjusting trade policies (Anderson and Nelgen, 2012). To investigate the impact of price fluctuations on trade policy coordination, a particular structure must be placed upon the social welfare function since the exploitation of terms of trade is not sufficient to explain this behavior. The terms-of-trade theory relates trade policy adjustments to trade volumes rather than to world price (Bagwell and Staiger, 1990, and below). So to introduce the observed reaction of trade policies to world price, it is necessary to consider other economic and political-economy motivations for time-varying trade policies.

This behavior can be perfectly rationalized when accounting for market failures in risk management. As a second-best policy, a countercyclical trade policy can be shown to play a role of insurance when factors are specific and consumers are not able to diversify their factor endowments as in Eaton and Grossman (1985). This argument has been used to justified time-varying trade barriers in many studies related to trade and uncertainty (see, e.g., Cassing et al., 1986, Gouel and Jean, forthcoming). However, it is often argued (e.g., Freund and Özden, 2008) that trade policies based on risk aversion require unrealistically high level of relative risk aversion to generate sizable interventions. This is slightly less true for staple food in developing countries as what matters is not the risk aversion *per se* but the product of risk aversion and budget share (Turnovsky et al., 1980), the latter being potentially quite high.

As these offsetting trade policies are used as well by developing and developed countries (Anderson and Nelgen, 2012), while in these latter the case for insurance through trade policies is much weaker, their existence is often explained more by political-economy considerations than by economic justifications (Anderson et al., 2013). It is, however, not clear which political-economy theory can account for this behavior. The Grossman and Helpman's (1994) protection for sale theory does not predict countercyclical protection (Swinnen, 2010). Its behavioral extension based on loss aversion by Freund and Özden (2008) and Tovar (2009) could account for price-insulating trade policies, but intervention in this framework would be one-sided: trade policy would be used to prevent losses to producers when prices decrease but not when they increase.

The loss-aversion framework could be made two-sided by introducing, in addition to the losses of specific factor owners, the losses of poor consumers from high food prices (such as in Giordani et al., 2012). This would be consistent with the conclusion of Arezki and Brückner (2011) and Barrett and Bellemare (2011), who show that social unrests are correlated with food price spikes, but not with episodes of highly volatile prices. Taking as reference situation the free-trade steady state, this would penalize both positive, for consumers' losses, and negative, for producers' losses, deviations from steady-state price. However, this approach does not lead to predictions compatible with stylized facts. Because of the diminishing sensitivity to losses in the loss-aversion framework, trade interventions would be relatively less important for very high prices than for prices just above the normal, a behavior for which there is no evidence (Anderson and Nelgen, 2012). In addition, the loss-aversion framework would have limited tractability in the context of countries interacting within a dynamic game.

Given that this paper focuses on the strategic interaction of countries that insulate their markets, we adopt a tractable reduced-form social welfare function that could account for the economic and political-economy motivations described above and that allows trade policies to vary countercyclically with international price according to stylized facts (Anderson and Nelgen, 2012). We assume that governments maximize their country's welfare, which is defined as the sum of producer's surplus, consumer's surplus and tariff revenue to which a quadratic term in the domestic price is added to account for the welfare cost of price volatility. $W(P, P^w, \varepsilon)$ and $W^*(P^*, P^w, \varepsilon^*)$ represent domestic and foreign country welfare, and are defined by

$$W\left(P^f, V^f, \tau, \tau^*\right) = \int_P^{a/b} D(p)\,\mathrm{d}p + P\varepsilon - (P - P^w)\left[\varepsilon - D(P)\right] - K\frac{(P-\bar{P})^2}{2}, \tag{6}$$

$$W^*\left(P^f, V^f, \tau, \tau^*\right) = \int_{P^*}^{a/b} D^*(p)\,\mathrm{d}p + P^*\varepsilon^* - (P^* - P^w)\left[\varepsilon^* - D^*(P^*)\right] - K\frac{(P^*-\bar{P})^2}{2}, \tag{7}$$

where $K \geq 0$ is a parameter characterizing the aversion to price risk, and $\bar{P}$ is a target price around which policy-makers wish prices to be stabilized. $\bar{P}$ is taken to be the steady-state, free-trade price, so the price when shocks are equal to their expectations and when countries do not use trade policies. Given the linearity of the model, the steady-state, free-trade price is also equal to the average price without intervention. For simplicity, the aversion to price risk and the target price are assumed to be identical in both countries allowing results to be symmetric.

For what follows it is useful to calculate the expression of the derivatives of W with respect to P and P^w:

$$W_P = -K(P-\bar{P}) - b(P-P^w), \tag{8}$$

$$W_{P^w} = \varepsilon - D(P). \tag{9}$$

The derivatives of W^* would give similar expressions.

3.2 Trade policies as function of world price

Before considering the Nash equilibrium, we analyze how trade policies react when countries maximize their social welfare function as defined above. To get the optimal reaction to world price changes, we maximize W over $\tau \leq 0$ and W^* over $\tau^* \geq 0$:

$$\frac{\mathrm{d}W}{\mathrm{d}\tau} = W_P\frac{\mathrm{d}P}{\mathrm{d}\tau} + W_{P^w}\frac{\mathrm{d}P^w}{\mathrm{d}\tau} = 0 \text{ if } \tau < 0, \text{ and } \frac{\mathrm{d}W^*}{\mathrm{d}\tau^*} = W^*_{P^*}\frac{\mathrm{d}P^*}{\mathrm{d}\tau^*} + W^*_{P^w}\frac{\mathrm{d}P^w}{\mathrm{d}\tau^*} = 0 \text{ if } \tau^* > 0,$$

which leads to:

$$\tau = \min\left[0, \frac{\overbrace{K(\bar{P}-P^w)}^{\text{Smoothing}} - \overbrace{(\varepsilon - a + bP^w)}^{\text{Market power}}}{K+2b}\right], \tag{10}$$

and to a similar expression for the foreign country trade policy.

This trade policy has two components. The first component obeys a smoothing motive. It is countercyclical and would tend to impose export subsidies when prices are below steady-state price and export taxes when prices are above steady-state price. The second exploits the country's market power. It leads to the use of export taxes to exploit market power on world price and, as is clear from the equation, this component is proportional to the trade volume at border price $(\varepsilon - D(P^w))$. For $K = 0$, this is the only rationale for intervention.[4]

3.3 The interior Nash equilibrium

Now, we characterize the interior Nash equilibrium and express all results as functions of P^f and V^f. From equation (10), best-response correspondences are given by

$$\tau_R\left(P^f, V^f, \tau^*\right) = \min\left[0, 2\frac{K\left(\bar{P} - P^f\right) - V^f}{K + 3b} + \frac{K + b}{K + 3b}\tau^*\right], \tag{11}$$

$$\tau_R^*\left(P^f, V^f, \tau\right) = \max\left[0, 2\frac{K\left(\bar{P} - P^f\right) + V^f}{K + 3b} + \frac{K + b}{K + 3b}\tau\right]. \tag{12}$$

For each country, the interior Nash trade policies present three possible regimes. For sufficiently low prices $(P^f \leq \bar{P} - bV^f/K(K + 2b))$, the unconstrained policy for the exporter would be to subsidize its exports, because it is prevented from doing it, it does not impose any trade barrier. In this case, the importer policy is set by (12) with $\tau = 0$. The opposite is true for sufficiently high prices $(P^f \geq \bar{P} + bV^f/K(K + 2b))$: no trade policy on the importer side and exporter trade policy determined by (11). For intermediate prices, trade policies in each country account for the intervention in the other country. This is summarized by the following expressions:

$$\tau_N\left(P^f, V^f\right) = \begin{cases} 0 & \text{if } P^f \leq \bar{P} - \frac{bV^f}{K(K+2b)}, \\ \frac{K\left(\bar{P} - P^f\right)}{b} - \frac{V^f}{K+2b} & \text{if } \left|\bar{P} - P^f\right| \leq \frac{bV^f}{K(K+2b)}, \\ 2\frac{K\left(\bar{P} - P^f\right) - V^f}{K+3b} & \text{if } P^f \geq \bar{P} + \frac{bV^f}{K(K+2b)}, \end{cases} \tag{13}$$

$$\tau_N^*\left(P^f, V^f\right) = \begin{cases} 2\frac{K\left(\bar{P} - P^f\right) + V^f}{K+3b} & \text{if } P^f \leq \bar{P} - \frac{bV^f}{K(K+2b)}, \\ \frac{K\left(\bar{P} - P^f\right)}{b} + \frac{V^f}{K+2b} & \text{if } \left|\bar{P} - P^f\right| \leq \frac{bV^f}{K(K+2b)}, \\ 0 & \text{if } P^f \geq \bar{P} + \frac{bV^f}{K(K+2b)}, \end{cases} \tag{14}$$

where the subscript N designates variables on the Nash equilibrium. We find again in these expressions the two components of smoothing and market power. Terms proportional to $\bar{P} - P^f$ relate to smoothing and terms proportional to V^f to market power. They behave very differently. Let us analyze them separately.

The market power components are of opposite sign in the two countries. Given world price equation (5), it means that for intermediate world price levels, when policies are unconstrained, these components are not affecting world price. The exporter tends to tax exports and the importer to tax imports. It reduces trade level, leaves world price unchanged, reduces price in the exporter, and increases price in the importer.

On the contrary, for intermediate world price levels, the component of trade policy motivated by

[4] With a small country, the optimal trade policy would be $\tau = \min\left[0, K\left(\bar{P} - P^w\right) / (K + b)\right]$. This is similar but slightly different from the smoothing component of (10). With respect to the smoothing objective, a small country reacts more to world price change than a big country, for which the use of countercyclical trade policies amplifies world price movement and so hurts its smoothing objective. However, when accounting for the terms-of-trade motivation, a big country adjusts more its trade policy with world price changes than a small country, because the ratio of the slopes of the trade policy rules with respect to world price is $K(K + 2b) / (K + b)^2$, which is always inferior to 1.

smoothing is equal across countries and does not affect domestic prices. Each country tries to bid more for the same commodity. In a situation of scarcity, the exporter increases its export tax and the importer decreases its tariff by the same amount, so the quantities allocated are the same. The terms of trade of the exporter improve to the expense of the importer, so a transfer has taken place from importing to exporting countries. The opposite is true in a situation of glut: the exporter decreases its export tax and the importer increases its tariff, so these smoothing policies lead to transfer from exporting to importing countries. These policy adjustments perfectly offset each other, so they are inefficient. This inefficiency of countercyclical trade policies at the global level was already emphasized by Bigman and Karp (1993), and Martin and Anderson (2012).

Martin and Anderson (2012) compare this inefficiency of the countercyclical component of trade policies to the collective-action problem that arises when a crowd stands up in a stadium to get a better view: when everybody is standing, one does not get a better view by standing up, but remaining seated is no longer an option. In our framework, this zone of compensation is not what may justify an international cooperative agreement, because the only aggregate welfare cost is related to the terms-of-trade part of intervention. Since the smoothing parts of trade policies compensate each other, they do not affect domestic prices but create income transfers associated with the terms-of-trade changes. Across time, these transfers compensate because the target price is also the average price. However, in our welfare framework, this volatility of income is not costly. The smoothing motivation for trade policies open the possibility for a trade agreement precisely when the policies do not compensate: for low or high free-trade world price when one country is constrained in its trade policy.

Given the use of this trade policy by the two countries, world price is given by

$$P_N^w\left(P^f,V^f\right)=P^f+\begin{cases}\frac{K\left(P^f-\bar{P}\right)+V^f}{K+3b} & \text{if } P^f\leq\bar{P}-\frac{bV^f}{K(K+2b)},\\ \frac{K\left(P^f-\bar{P}\right)}{b} & \text{if } \left|\bar{P}-P^f\right|\leq\frac{bV^f}{K(K+2b)},\\ \frac{K\left(P^f-\bar{P}\right)-V^f}{K+3b} & \text{if } P^f\geq\bar{P}+\frac{bV^f}{K(K+2b)}.\end{cases} \tag{15}$$

With respect to free trade, world price will be increased by the trade policies when free-trade world price is above the steady-state price and decreased when it is below (see figure 1). These trade policies increase world price variance with respect to the free-trade situation. This increased variance is caused by the smoothing motivation (the world price variance would be the same as in free trade if K equal 0).

The two special cases of pure aggregate risk and pure idiosyncratic risk present interesting contrasts to help in analyzing these policies.

Pure aggregate risk In a situation where $\varepsilon-\varepsilon^*$ is a constant, there is only an aggregate supply risk, but no idiosyncratic risk. This leads to a constant free-trade trade volume, but a volatile free-trade world price, and according to (13)–(14), changes in trade policy are only explained by the smoothing motivation. Considerations of strategic interactions and market power are not absent, though. For intermediate world prices, the slope of the trade policy rule with respect to free-trade world price is $-K/b$, while it would be smaller at $-K/(K+b)$ in a small country. Indeed in the Nash equilibrium, countries adjust more their trade policies to world price because they try to compensate their partner's trade policy, when this latter is active.

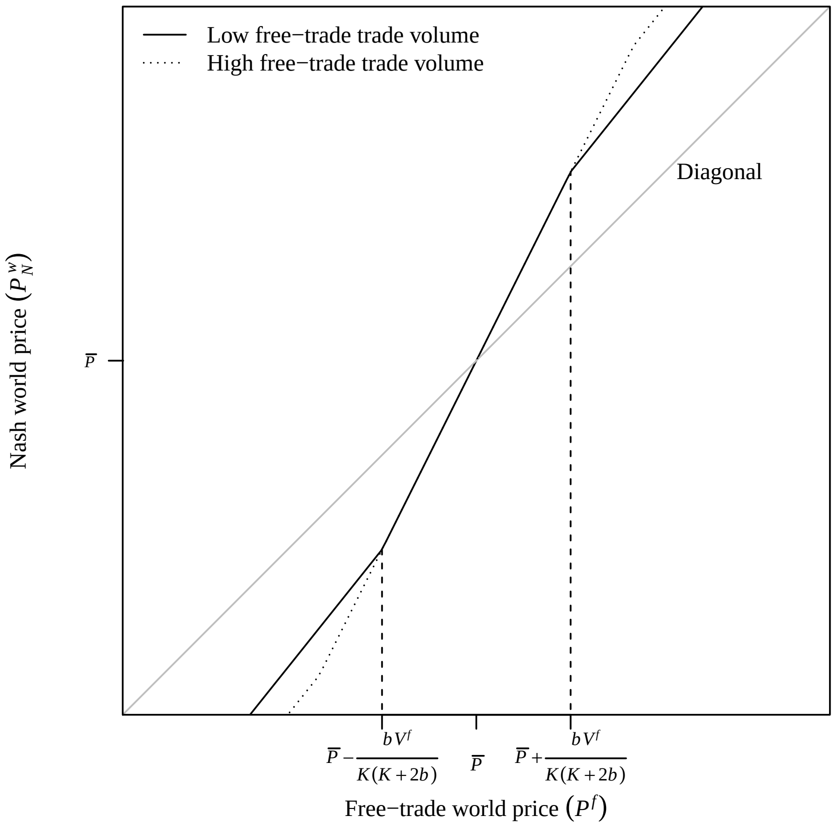

Figure 1. Interior Nash world price for two levels of free-trade trade volume

Pure idiosyncratic risk If $\varepsilon + \varepsilon^*$ is a constant, there is no aggregate risk, only idiosyncratic risk (this is the situation analyzed in Newbery and Stiglitz, 1984, and Bagwell and Staiger, 1990). Free-trade world price would be constant and the smoothing component of trade policies would not change. The change in trade policies coming from the terms-of-trade motivation appears to be in conflict with the desire for smoothing. Without trade policy intervention, price would be constant, but potential terms-of-trade gains compel countries to intervene. This creates a trade-off between smoothing and terms-of-trade motivation. It appears in equations (13)–(14) in the slope of trade policy with respect to the free-trade trade volume: for intermediate world price, without the smoothing motivation in the social welfare function, the slope would be $1/2b$, whereas it is $1/(K+2b)$. The slope is reduced by the smoothing motive, since the pursuit of terms-of-trade gains goes against it.

One intuition about trade policies motivated by price smoothing is that they may hinder international sharing of agricultural production risk. Agricultural production is much more volatile at the country level than at the world level, because the pooling of all the idiosyncratic weather shocks leads to a much more stable aggregate production. The two extreme cases analyzed above show that the smoothing component of trade policies does not try to prevent risk sharing, it is even equal to zero when there is only idiosyncratic risk. Smoothing-related trade policies are only motivated by aggregate shocks that affect world prices.

3.4 The autarky equilibria

Now, we consider the Nash equilibria that correspond to autarky. If $-\tau \geq 2V^f/b$ or $\tau^* \geq 2V^f/b$ then, whatever the value of the other country trade policy, condition (3) does not hold and autarky prevails. So there is a set of Nash equilibria without trade for any trade tax pair in which one of the tax exceeds in absolute value $2V^f/b$.

4 International cooperative agreement

We now consider that the countries interact repetitively, which enables them to coordinate on more cooperative policies. In this dynamic game, based on the observed state variables, countries decide at each period their trade policy. They coordinate on protection levels smaller than in the static game, but if one country deviates from the cooperative protection levels, they forever revert to the interior Nash equilibrium.

For each country, there is a trade-off between the short-run gains from deviation and the long-run losses from returning to the Nash equilibrium. This implies that for ensuring countries have not incentive to deviate, the following incentive compatibility constraints (IC) have to be respected (to facilitate the exposition, the welfare functions are now expressed as function of P^f, V^f, τ and τ^*, which is possible by substituting out P, P^* and P^w using equations (1) and (5), and ε and ε^* using the definition of P^f and V^f):

$$\mathrm{E}_t \sum_{i=0}^{\infty} \beta^i W\left(P^f_{t+i}, V^f_{t+i}, \tau_{t+i}, \tau^*_{t+i}\right) \geq W_D\left(P^f_t, V^f_t, \tau^*_t\right) + \frac{\beta}{1-\beta}\mathrm{E}W_N, \tag{16}$$

$$\mathrm{E}_t \sum_{i=0}^{\infty} \beta^i W^*\left(P^f_{t+i}, V^f_{t+i}, \tau_{t+i}, \tau^*_{t+i}\right) \geq W^*_D\left(P^f_t, V^f_t, \tau_t\right) + \frac{\beta}{1-\beta}\mathrm{E}W^*_N, \tag{17}$$

where $W_D\left(P^f_t, V^f_t, \tau^*_t\right) = \max_{\tau_t \leq 0} W\left(P^f_t, V^f_t, \tau_t, \tau^*_t\right)$ is the welfare in case of deviation, so when the country's trade policy is given by its best-response correspondence (11); $\mathrm{E}W_N \equiv \mathrm{E}W\left(P^f, V^f, \tau_N, \tau^*_N\right)$ is the unconditional expected welfare on the Nash equilibrium; and β is the discount parameter. These ICs convey the lack of commitment of each country. They do not commit to respect cooperative policies whatever the situation. The cooperation is possible as long as in any situation the cooperative policy is such that it satisfies these constraints. The equilibrium has to be self-enforcing.

We analyze the most cooperative sub-game perfect Nash equilibrium, so the policies are only function of payoff relevant variables, the current state variables, not on past history.

We are looking for the most cooperative sub-game perfect equilibrium. Another way to see this problem is to consider that this is the problem of a planner that tries to find the time-consistent trade policies (τ and τ^* as functions of P^f and V^f) that maximize aggregate welfare while satisfying the countries' participation constraints. This amounts to solve the following maximization problem:

$$\begin{aligned}\max_{\tau_t \leq 0, \tau^*_t \geq 0} & W\left(P^f_t, V^f_t, \tau_t, \tau^*_t\right) + W^*\left(P^f_t, V^f_t, \tau_t, \tau^*_t\right) + \\ & \mathrm{E}_t \sum_{i=1}^{\infty} \beta^i \left[W\left(P^f_{t+i}, V^f_{t+i}, \tau_{t+i}, \tau^*_{t+i}\right) + W^*\left(P^f_{t+i}, V^f_{t+i}, \tau_{t+i}, \tau^*_{t+i}\right)\right]\end{aligned} \tag{18}$$

subject to the participation constraints, (16)–(17).

Given that the problem has no intrinsic dynamics (the state variables, ε and ε^*, are i.i.d.) and that we are focusing on the sub-game perfect equilibrium, all expectations terms are actually constants that are function of the optimal cooperative policy.

Constraining trade policies to be taxes and associating positive Lagrange multipliers, μ_t and μ_t^*, to equations (16) and (17), the above problem gives the following first-order conditions (to simplify notations, social welfare functions under cooperation are expressed as functions of time, $W(t) \equiv W\left(P_t^f, V_t^f, \tau_t, \tau_t^*\right)$, and the cooperative unconditional expected welfare is noted $\mathrm{E}W_C \equiv \mathrm{E}W\left(P^f, V^f, \tau, \tau^*\right)$):[5]

$$\tau_t : \tau_t \leq 0 \perp (1+\mu_t)\frac{\partial W\left(P_t^f, V_t^f, \tau_t, \tau_t^*\right)}{\partial \tau_t} + (1+\mu_t^*)\frac{\partial W^*\left(P_t^f, V_t^f, \tau_t, \tau_t^*\right)}{\partial \tau_t} \geq \mu_t^* \frac{\partial W_D^*\left(P_t^f, V_t^f, \tau_t\right)}{\partial \tau_t}, \tag{19}$$

$$\tau_t^* : \tau_t^* \geq 0 \perp (1+\mu_t^*)\frac{\partial W^*\left(P_t^f, V_t^f, \tau_t, \tau_t^*\right)}{\partial \tau_t^*} + (1+\mu_t)\frac{\partial W\left(P_t^f, V_t^f, \tau_t, \tau_t^*\right)}{\partial \tau_t^*} \leq \mu_t \frac{\partial W_D\left(P_t^f, V_t^f, \tau_t^*\right)}{\partial \tau_t^*}, \tag{20}$$

$$\mu_t : \mu_t \geq 0 \perp W(t) + \frac{\beta}{1-\beta}\mathrm{E}W_C \geq W\left(P_t^f, V_t^f, \tau_R\left(P_t^f, V_t^f, \tau_t^*\right), \tau_t^*\right) + \frac{\beta}{1-\beta}\mathrm{E}W_N, \tag{21}$$

$$\mu_t^* : \mu_t^* \geq 0 \perp W^*(t) + \frac{\beta}{1-\beta}\mathrm{E}W_C^* \geq W^*\left(P_t^f, V_t^f, \tau_t, \tau_R^*\left(P_t^f, V_t^f, \tau_t\right)\right) + \frac{\beta}{1-\beta}\mathrm{E}W_N^*. \tag{22}$$

μ and μ^* play the role of the relative weighting of countries in world welfare. It may change at each period depending on which participation constraint is binding. When one country's IC is binding, its welfare weight becomes positive justifying its deviation from the first-best trade policy (i.e., from free trade).

Given that Nash trade policies and best-response functions are kinked, and that policies may be occasionally constrained to be taxes, a complete analytical characterization of this problem is out of reach or at least too cumbersome to be of interest.[6] We provide below an interpretation of these equations in various situations depending on which constraint is binding, and we rely later on numerical simulations to provide further insights about the solution.

The possibility to observe binding ICs in one or two countries depends on the value assumed for the discount parameter. If we define $\omega \equiv \mathrm{E}W_C - \mathrm{E}W_N$, the long-run benefits of cooperation and $\Omega\left(P^f, V^f, \tau, \tau^*\right) \equiv W\left(P^f, V^f, \tau_R\left(P^f, V^f, \tau^*\right), \tau^*\right) - W\left(P^f, V^f, \tau, \tau^*\right)$ the short-run gains from deviation, the two ICs are never binding when the discount parameter is superior to

$$\bar{\beta} = \max\left[\frac{\Omega\left(P_M^f, V_M^f, 0, 0\right)}{\Omega\left(P_M^f, V_M^f, 0, 0\right) + \omega}, \frac{\Omega^*\left(P_m^f, V_M^f, 0, 0\right)}{\Omega^*\left(P_m^f, V_M^f, 0, 0\right) + \omega^*}\right], \tag{23}$$

where P_m^f, P_M^f and V_M^f are, respectively, the minimum, and maximum of free-trade world price and the maximum of free-trade trade volume. The value of $\bar{\beta}$ can be calculated as an intricate function of the distributions of supply shocks and the various behavioral parameters. The function is complicated because it does not depend only on the moments of the distributions but also on the probabilities of the three

[5]Complementarity conditions in what follows are written using the "perp" notation ($\perp$). This means that both inequalities must hold, and at least one must hold with equality.

[6]See Bagwell and Staiger (1990) for the analytical characterization of a similar but simpler problem.

regimes defined above for the Nash behavior.

No binding IC With $\mu_t = \mu_t^* = 0$, equations (19) and (20) are identical to what they would be if the maximization were not subject to the ICs, so for globally efficient trade policies. Equation (19) gives $\tau_t \leq 0 \perp \tau_t^* - \tau_t \leq 0$, which is only compatible with $\tau_t = \tau_t^* = 0$. Thus, when no participation constraint is binding, the cooperative policy is free trade. Note, however, that this is a consequence of the restriction of the analysis to tax policies. Without restriction, the solution would be $\tau_t = \tau_t^*$, which is compatible with free trade, but also with countercyclical trade policies.

Binding ICs For a not too high discount factor, the efficient trade policy does not satisfy the ICs for all possible shocks, hence the need for state-contingent welfare weights to ensure that trade policies satisfy the ICs. There are three possible situations: IC binding in home, in foreign, or in both countries. This is in contrast with Bagwell and Staiger (1990) where only the situation of both ICs binding was possible because the only motivation for trade policies was the terms-of-trade gains and they show up when trade volumes are important, which increases similarly the temptation to deviate in the two countries. Here we have in addition the smoothing motivation, which has asymmetric effects. The temptation to deviate will be higher for exporters in periods of high prices and for importers in periods of low prices.

IC binding in one country If we consider the case of the IC binding in home, we would have $\mu_t > 0$ and $\mu_t^* = 0$ (the explanation would be similar for foreign). This leads equation (19) to be simplified to

$$\tau_t : \tau_t \leq 0 \perp (1+\mu_t)\frac{\mathrm{d}W(t)}{\mathrm{d}\tau_t} + \frac{\mathrm{d}W^*(t)}{\mathrm{d}\tau_t} \geq 0,$$

where it is clear that the welfare weight of home has been increased to the detriment of foreign. If we assume that $\tau_t^* = 0$ and $\tau_t < 0$, Equation (19) then gives

$$\tau_t = \mu_t \frac{K\left(\bar{P} - P_t^f\right) - V_t^f}{K + b + (K+3b)\,\mu_t/2}, \tag{24}$$

which is indeed negative for free-trade prices higher than $\bar{P}$.

Both ICs binding If welfare weights are strictly positive, the terms on the right-hand side of equations (19) and (20) may matter. They account for the fact that when a country changes its trade policy, it changes also its partner's incentives to deviate. This is only effective if the partner country's IC is binding. If not, a country does not have to worry about its partner's incentives until it becomes binding. Given equations (13) and (14) characterizing the behavior in Nash, we should expect the ICs to be both binding for intermediate free-trade price level and sufficiently high free-trade trade volume. For high or low free-trade world price, deviation should come respectively from the exporter and the importer. And for intermediate price level, this is the terms-of-trade motivation, which will compel both countries to deviate (as in Bagwell and Staiger, 1990).

4.1 Cooperation under a symmetric price distribution

The following numerical results (see the supplementary appendix for details on the numerical method) should be considered as mere illustrations of the model behavior, but the numbers should not be given a too serious interpretation as our framework has been kept voluntarily simple (for example, we have neglected supply reaction) and we have large uncertainties about appropriate values for behavioral parameters.

We focus the discussion of numerical results on a situation of pure aggregate risk, in which the smoothing motivation for trade intervention is dominant. Since in this case, free-trade price summarizes the state of the system, this facilitates results interpretation by permitting diagrammatic representations. In the alternative configuration of pure idiosyncratic risk, the results are very close to Bagwell and Staiger (1990). The only difference being that our static level of protection is less important as the smoothing objective goes against the exploitation of terms-of-trade gains. In this case, trade policies are of equal intensity but of opposite sign. In a repeated game, for a sufficiently high discount parameter, the threat of retaliations allows to coordinate on free trade. And for a lower discount parameter, deviations from free trade cannot be excluded. They occur at the same moment for both countries: when free-trade volume is high, because a higher free-trade volume increases the potential terms-of-trade gains and the incentive to deviate.

To choose relevant values for K, the parameter of aversion to price risk, we note that although the quadratic term in the social welfare functions is only meant to introduce in a tractable way additional concavity, it could also be interpreted as the difference between the second-order approximation to the equivalent variation of a risk-averse consumers and its surplus, so it would be the welfare term accounting for non-zero risk aversion and income elasticity. From Turnovsky et al. (1980), K would in this case be equal to $\gamma(R-\nu)D(\bar{P})/\bar{P}$, where γ, R and ν are, respectively, values at steady-state of the commodity budget share, relative risk aversion to income and income elasticity. This would be positive if risk aversion is higher than income elasticity, which seems reasonable for staple food products. This would represent an approximation of the social welfare of an incomplete markets economy in which risk-averse consumers cannot insure against food price risk (see Gouel and Jean, forthcoming, for such a situation). We assume $K = 0.3$, which could correspond to a 15% budget share, a relative risk aversion equal to 2, and a null income elasticity.

Figure 2 displays the cooperative and non-cooperative trade policies for various discount parameters. The parameters are chosen such that at steady state demand is equal in both countries to 1 and trade to 0.2. The steady-state world price is taken to be 1, and using a demand elasticity of -0.3 and a uniform distribution for ε over $[1.09, 1.31]$ the coefficient of variation of world price is equal to 21%. Non-cooperative Nash policies (dash-dotted curves) are constrained by their restriction to being taxes. For high world prices, the importing country would like to use import subsidy. When this constraint binds, the exporting country trade policy decreases its slope with respect to world price, because it does not need to react as much as before to world price, its policy being no longer offset by its partner. This change in slope when only one country is using its trade policy occurs also in repeated games.

When the game is repeated, more cooperative policies can be achieved, although it is not possible to always exclude deviations from free trade for high and low free-trade world price. Cooperative policies are represented in figure 2 for various discount parameters in solid lines. There are three possible regimes. (i) For a sufficiently high discount parameter, $\beta \geq \bar{\beta} = 0.72$, free trade can be sustained by the threat of retaliation whatever the levels of the stochastic shocks. (ii) For a lower value of discount parameter, ICs

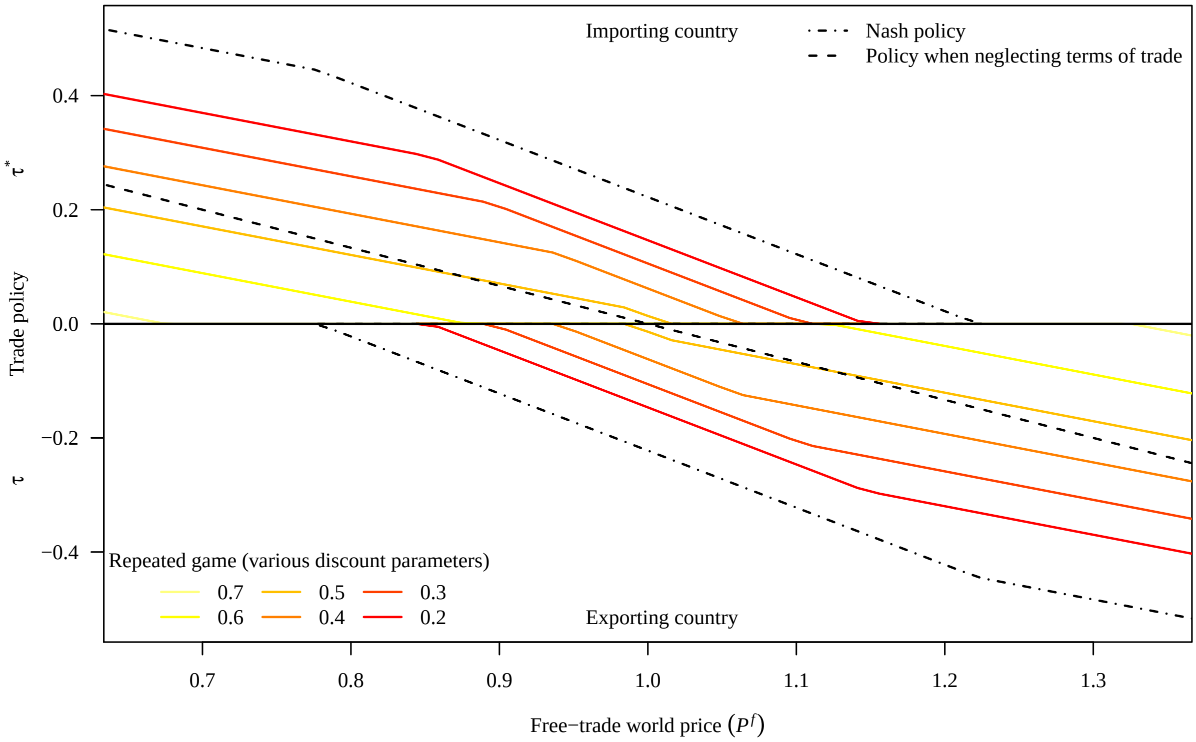

Figure 2. Cooperative and non-cooperative trade policies. Parameters values: $a = 1.3$, $b = 0.3$, $K = 0.3$, ε follows a continuous uniform distribution defined over [1.09,1.31], ε^* equal to $\varepsilon - 0.4$.

start to bind for low and high world prices. However, they are not binding at the same time; each country is allowed to deviate from free trade at separate moments. The exporter deviates when world price is high by taxing exports and the importer when world price is low by taxing imports. Outside the regions where ICs are binding, the cooperative trade policy is free trade. (iii) For lower discount parameter values, ICs bind more often and can be binding at the same time. Note that the discount parameter should not be interpreted as a market discount rate, but as the discount rate of policy-makers for which the future may not extend much longer than the next election.

4.2 Cooperation under an asymmetric price distribution

Some of the previous results are a consequence of the symmetry of the problem. Beyond the perfect symmetry of the countries, what seems crucial is the symmetry of the price distribution, which is in itself an outcome of many assumptions. In reality, commodity prices are positively skewed (Deaton and Laroque, 1992), a feature often explained by competitive storage, which would have been too challenging to integrate in a repeated game approach. Price skewness could also be explained in other ways. A convex demand function could, for example, create skewness in price distribution. This is precisely the effect of storage, which convexifies the demand by adding to final demand a demand for stocks at low prices (Wright and Williams, 1982). We have also noted before that we have assumed the cost of deviating from the target price to be symmetric, but it could be argued that many countries care more about high prices than low prices, which would skew trade policies and so the resulting price distribution (Arezki and Brückner, 2011, Barrett and Bellemare, 2011). A positive price skewness could also arise from negatively skewed yield.

The lack of symmetry of the price distribution may be crucial because it affects the distribution of welfare between the two countries and, consequently, what could be expected from a cooperation ensured by the threat of retaliations. To analyze this we introduce asymmetry by assuming that yields are negatively skewed. This does not involve any change in the equations. They hold equally for symmetric and asymmetric shocks. Results would be symmetric with positively-skewed yields, but negatively-skewed yields imply positively-skewed prices, as is observed in price data.

The asymmetry affects the respective costs of the trade war between the exporting and the importing country. In the static game (0 discount parameter in figure 3), the interior Nash equilibrium is more costly to the exporting country than to the importing country. This is explained by the price distribution (see figure 4). Upward price spikes are more common than downward price spikes, so we observe more often large deviations from the exporter than large deviations from the importer. However, much of the price distribution is concentrated in prices below the target price, with a significant share in a region in which the exporting country is not applying export restrictions. So, on average, the exporting country suffers more from the trade war, because it is more often constrained in its trade policies.

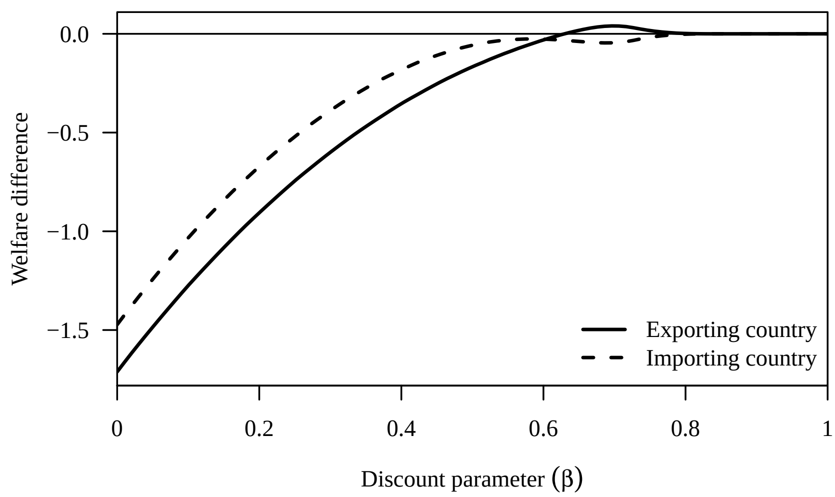

Figure 3. Difference between expected welfare under coordination and free trade (as percentage of the steady-state budget spent by consumers on this commodity). Parameters values follow those used for figure 2 except for ε. Its distribution has the same mean and standard deviation than before, but follows a beta distribution of shape parameters 6 and 2, rescaled and translated between the bounds 0.87 and 1.31; ε^* is equal to $\varepsilon - 0.4$.

In a repeated game, these lower losses for the importing country hold for low to medium discount rate (until $\beta = 0.6$), because cooperation does not change the fact that the exporting country is more often constrained in its trade policies. However, the relationship between the discount parameter and difference between expected welfare under coordination and under free trade does not appear to be monotonic. For a high enough discount rate, both countries do not use trade policies and their welfare is equal to its free-trade value. But before reaching the first-best welfare there is an interval over the discount rate for which the exporting country welfare exceeds the free-trade welfare and the importing country welfare is decreasing. For this intermediate discount rate values, the threat to go back to the trade war exceeds the short-run gains from deviation for most free-trade world price and free trade prevails for most supply shocks. In particular, for the importing country, the gains from deviation are never really high since the free-trade world price does not reach very low values. On the contrary, for the exporting country, the gains from deviation can occasionally be high because of the possibility of high world prices. In these

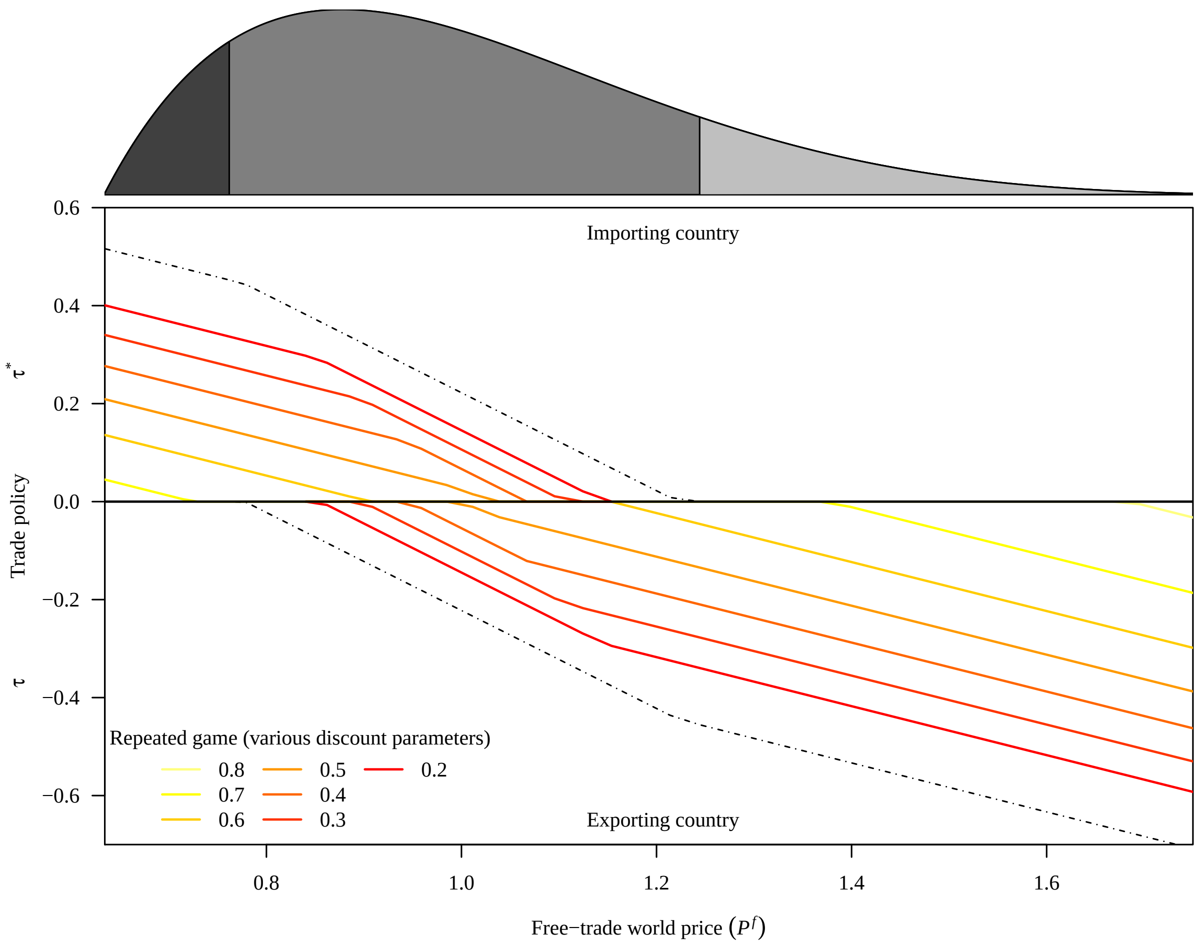

Figure 4. Trade policies under asymmetric price distribution. Density of free-trade world price above the plot, with a distinction between the regions where, in the Nash, the importing country is the only country to intervene, where both intervene and where the exporting country is the only one to intervene. See figure 3 for parameters values.

cases, when the discount rate is not too high, the IC of the exporter is binding and compels it to deviate from the first-best. This situation is asymmetrical as is clear in figure 4 when $\beta = 0.8$: the discount rate is sufficiently high to deter any deviation from first best for the importer, but not sufficiently high for the exporter given that the price distribution is skewed. Since the exporter is occasionally using trade policies, while the importer is not, the former enjoys a welfare level above what it could get in free trade at the expense of its partner.

5 Conclusion

Considering that governments care for domestic food price volatility and use trade policy instruments to stabilize their food markets, this paper analyzes the extent of international trade policy cooperation that is sustainable by the threat to return to the static interior Nash equilibrium. This paper differs from the related literature (Bagwell and Staiger, 1990, 2003) by considering that governments adjust trade policy in order to manipulate their terms of trade, but also to stabilize their domestic food prices. It also stresses the important distinctions between aggregate and idiosyncratic supply shocks for trade policy interventions. The terms-of-trade motivation is related only to idiosyncratic shocks (i.e., shocks to free-trade trade volumes) and do not lead to any trade policy adjustments in case of aggregate shocks (i.e., shocks to free-trade world price), which are an important driver of actual trade policy adjustments for food products (Anderson and Nelgen, 2012). On the contrary, the smoothing motivation is related only to aggregate shocks and would not hinder the risk sharing of idiosyncratic supply shocks.

This work displays a standard feature of self-enforcing trade agreements: the need for active trade policies in periods of severe shocks to maintain the incentives to cooperate in every states of nature. While repeated interactions allow countries to coordinate on cooperative trade policies, periods of unusually high trade volume, or very low or very high prices are periods of deviation from free trade. So even in a cooperative agreement, it may not be possible to completely alleviate countercyclical trade policies. These deviations from first best differ from previous literature in that because of the smoothing motivation deviations are asymmetric: exporters deviate when world price is high and importers deviate when world price is low.

Policy discussions have devoted a lot of attention to export restrictions and their role in the recent food price spikes. To prevent future price spikes, many authors have advocated for WTO disciplines on export restrictions, which are today very weakly regulated. In this paper, export restrictions do not play a more important role that tariffs. The former are the policy used by exporters to protect themselves from international scarcity and the latter the policy used by importer, but they both contribute to shift volatility to partners' markets.

However despite this apparent symmetry between the trade policy instruments, export restrictions under repeated interactions may be more difficult to avoid than tariffs because of the asymmetry of the price distribution. Commodity prices are positively skewed and prices are concentrated below the mean, but with occasional spikes. This matters a lot in a self-enforcing agreement, because it means that the exporter will have larger incentives to deviate from free trade than an importer. In this light, export restrictions may be more difficult to discipline in trade agreements than tariffs, and the reluctance of food exporting countries to open negotiations on this issue may convey their inability to commit not to using export restrictions given the incentives they face during food price spikes.

Computational details

The results were obtained using GAMS 23.9.5 and solved using the mixed complementarity solver `PATH` (Dirkse and Ferris, 1995) on a PC running Windows 7. Further technical details are available in a supplementary appendix and the programs code.

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Trade policy coordination and food price volatility
Numerical implementation

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June 26, 2014

This appendix gathers all the equations that define the cooperative policies and describes how the model is solved numerically. Since all the variables on the interior Nash equilibrium are characterized analytically by equations (1), (6)–(7), (13)–(14), and (15), this appendix focuses on the dynamic game. The problem is implemented numerically in GAMS version 23.9.5 and solved using the mixed complementarity solver PATH (Dirkse and Ferris, 1995), with a precision of 10^{-7}. Since the model has no intrinsic dynamics, there is no need to consider several periods. However, the model has to be solved over various supply shocks to allow for the calculation of expectations. The shocks on which the model is solved are chosen through Gaussian quadratures,[1] which define sets of pairs $\{(\varepsilon_i, \varepsilon_i^*), w_i\}$ in which $(\varepsilon_i, \varepsilon_i^*)$ represents a possible realization of shocks and w_i the associated probability. In the following, the mathematical notations follow the paper except for the time index, which is substituted by i or j, which index possible shocks realizations. The superscript D is used to designate situations of deviation from the cooperative policies.

The expected welfare under Nash ($\mathrm{E}W_N$ and $\mathrm{E}W_N^*$), free-trade world price (P_i^f) and free-trade trade volume (V_i^f) are calculated from their analytical expressions. Other variables solve the following set of complementarity equations, in which for compactness some functions are introduced and defined later:

$$P_i^w : P_i^w = P_i^f - \frac{\tau_i + \tau_i^*}{2}, \tag{A1}$$

$$P_i : P_i = P_i^w + \tau_i, \tag{A2}$$

$$P_i^* : P_i^* = P_i^w + \tau_i^*, \tag{A3}$$

$$W_i : W_i = \int_{P_i}^{a/b} D(p)\,\mathrm{d}p + P_i\varepsilon_i - (P_i - P_i^w)\left[\varepsilon_i - D(P_i)\right] - K\frac{\left(P_i - \bar{P}\right)^2}{2}, \tag{A4}$$

$$W_i^* : W_i^* = \int_{P_i^*}^{a/b} D^*(p)\,\mathrm{d}p + P_i^*\varepsilon_i^* - (P_i^* - P_i^w)\left[\varepsilon_i^* - D^*(P_i^*)\right] - K\frac{\left(P_i^* - \bar{P}\right)^2}{2}, \tag{A5}$$

$$\tau_i : \tau_i \le 0 \perp (1+\mu_i)\frac{\mathrm{d}W(i)}{\mathrm{d}\tau_i} + (1+\mu_i^*)\frac{\mathrm{d}W^*(i)}{\mathrm{d}\tau_i} \ge \mu_i^* \frac{\mathrm{d}W^*\left(P_i^f, V_i^f, \tau_i, \tau_R^*\left(P_i^f, V_i^f, \tau_i\right)\right)}{\mathrm{d}\tau_i}, \tag{A6}$$

$$\tau_i^* : \tau_i^* \ge 0 \perp (1+\mu_i^*)\frac{\mathrm{d}W^*(i)}{\mathrm{d}\tau_i^*} + (1+\mu_i)\frac{\mathrm{d}W(i)}{\mathrm{d}\tau_i^*} \le \mu_i \frac{\mathrm{d}W\left(P_i^f, V_i^f, \tau_R\left(P_i^f, V_i^f, \tau_i^*\right), \tau_i^*\right)}{\mathrm{d}\tau_i^*}, \tag{A7}$$

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[1] Gaussian quadrature are generated using the functions available in the MATLAB toolbox CompEcon (Miranda and Fackler, 2002).

$$\mu_i : \mu_i \geq 0 \perp W_i + \frac{\beta}{1-\beta}\sum_j w_j W_j \geq W_i^D + \frac{\beta}{1-\beta}\,\mathrm{E}\,W_N, \tag{A8}$$

$$\mu_i^* : \mu_i^* \geq 0 \perp W_i^* + \frac{\beta}{1-\beta}\sum_j w_j W_j^* \geq W_i^{*D} + \frac{\beta}{1-\beta}\,\mathrm{E}\,W_N^*, \tag{A9}$$

$$W_i^D : W_i^D = \int_{P_i^D}^{a/b} D(p)\,\mathrm{d}p + P_i^D \varepsilon_i - \left(P_i^D - P_i^{wD}\right)\left[\varepsilon_i - D\left(P_i^D\right)\right] - K\frac{\left(P_i^D - \bar{P}\right)^2}{2}, \tag{A10}$$

$$W_i^{*D} : W_i^{*D} = \int_{P_i^{*D}}^{a/b} D^*(p)\,\mathrm{d}p + P_i^{*D} \varepsilon_i^* - \left(P_i^{*D} - P_i^{w*D}\right)\left[\varepsilon_i^* - D^*\left(P_i^{*D}\right)\right] - K\frac{\left(P_i^{*D} - \bar{P}\right)^2}{2}, \tag{A11}$$

$$\tau_i^D : \tau_i^D \leq 0 \perp \tau_i^D \leq 2\frac{K\left(\bar{P} - P_i^{wf}\right) - V_i^f}{K+3b} + \frac{K+b}{K+3b}\tau_i^*, \tag{A12}$$

$$\tau_i^{*D} : \tau_i^{*D} \geq 0 \perp \tau_i^{*D} \geq 2\frac{K\left(\bar{P} - P_i^{wf}\right) + V_i^f}{K+3b} + \frac{K+b}{K+3b}\tau_i, \tag{A13}$$

$$P_i^D : P_i^D = P_i^{wD} + \tau_i^D, \tag{A14}$$

$$P_i^{*D} : P_i^{*D} = P_i^{w*D} + \tau_i^{*D}, \tag{A15}$$

$$P_i^{wD} : P_i^{wD} = P_i^f - \frac{\tau_i^D + \tau_i^*}{2}, \tag{A16}$$

$$P_i^{w*D} : P_i^{w*D} = P_i^f - \frac{\tau_i + \tau_i^{*D}}{2}. \tag{A17}$$

From equations (8) and (9), we have

$$\frac{\mathrm{d}W(i)}{\mathrm{d}\tau_i} = \frac{-K\left(P_i - \bar{P}\right) - b\left(P_i - P_i^w\right) - \varepsilon_i + D\left(P_i\right)}{2}, \tag{A18}$$

$$\frac{\mathrm{d}W^*(i)}{\mathrm{d}\tau_i} = \frac{K\left(P_i^* - \bar{P}\right) + b\left(P_i^* - P_i^w\right) - \varepsilon_i^* + D^*\left(P_i^*\right)}{2}, \tag{A19}$$

$$\frac{\mathrm{d}W(i)}{\mathrm{d}\tau_i^*} = \frac{K\left(P_i - \bar{P}\right) + b\left(P_i - P_i^w\right) - \varepsilon_i + D\left(P_i\right)}{2}, \tag{A20}$$

$$\frac{\mathrm{d}W^*(i)}{\mathrm{d}\tau_i^*} = \frac{-K\left(P_i^* - \bar{P}\right) - b\left(P_i^* - P_i^w\right) - \varepsilon_i^* + D^*\left(P_i^*\right)}{2}. \tag{A21}$$

Using the envelop theorem

$$\frac{\mathrm{d}W^*\left(P_i^f, V_i^f, \tau_i, \tau_R^*\left(P_i^f, V_i^f, \tau_i\right)\right)}{\mathrm{d}\tau_i} = \frac{\partial W^*\left(P_i^f, V_i^f, \tau_i, \tau_R^*\left(P_i^f, V_i^f, \tau_i\right)\right)}{\partial \tau_i}, \tag{A22}$$

$$= \frac{K\left(P_i^{*D} - \bar{P}\right) + b\left(P_i^{*D} - P_i^{w*D}\right) - \varepsilon_i^* + D^*\left(P_i^{*D}\right)}{2}, \tag{A23}$$

and similarly

$$\frac{\mathrm{d}W\left(P_i^f, V_i^f, \tau_R\left(P_i^f, V_i^f, \tau_i^*\right), \tau_i^*\right)}{\mathrm{d}\tau_i^*} = \frac{K\left(P_i^D - \bar{P}\right) + b\left(P_i^D - P_i^{wD}\right) - \varepsilon_i + D\left(P_i^D\right)}{2}. \tag{A24}$$

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