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Abstract

Trade has become the main mode of transport for many invasive species including diseases and agricultural pests. Most species are brought to their new homes unintentionally, which constitute a market failure rooted in international trade. Unless it is practical to drive invasion risk to zero, the external costs may justify a tariff. In this paper we analyze the political process likely to govern the formation of tariffs so justified, using a straightforward incorporation of an invasive species externality into Grossman and Helpman's well-known political economy model. We show our measure of disguised protectionism—the gap between the optimal tariff and that set in the equilibrium of the political economy game—is equal to the tariff that would be set if there were no invasive species and no international disciplines on trade policy. The informational needs required to distinguish disguised protectionism from legitimate public-goods protection are formidable.

Key Words: invasive species, protectionism, tariff, political economy

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Michael Margolis and Jason F. Shogren*

1. Introduction

As humans traverse the globe more swiftly, we have become the main mode of transportation for other species. One estimate suggests that 50,000 nonnative species now live in just the United States (see Pimentel et al. 2000). Most creatures introduced into alien environments die without a trace, and some become valued crops or ornaments. But some invasive species are diseases, some are agricultural pests, and some become major threats to the ecosystems. People only now are beginning to appreciate the scope and severity of the problems posed by this last class. Exotic species are the second most commonly cited cause of extinction threats (after land-use changes) and a source of threats to water quality, navigability, and other ecosystem services (OTA 1993; Sandlund et al. 1999). At present, species that have not yet been shown to cause problems can be freely imported into most countries. Most species, however, are brought to their new homes unintentionally in ballast water, packing material, and cargo (Jenkins 1996). The resulting invasions constitute a market failure rooted in international trade.

Economists generally agree that market failures should be corrected as close as possible to their source. Consider pollution from hog farming for example. While pollution could be alleviated by subsidizing some combination of other activities to attract labor and machinery away from hog-farms, most economists agree that a tax on hog farmers is better, and a tax that varies with level of emissions—a Pigovian tax—is ideal. Similarly, although the theory of the second best implies that trade restrictions may improve national welfare if there is any domestic market failure, economists almost always respond by urging a solution more targeted to the failure.

Invasive species are among a relatively small group of market failures the source of which is trade itself (although it is never explicitly discussed in Copeland and Taylor's 2003 book on trade and the environment). Other examples include pollution from ships and the

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opportunity for smuggling of contraband materials or military (i.e., terrorist) personnel. In these cases reducing trade *is* the solution closest to the source of the failure, unless it is possible to monitor the harmful activity itself. That might be possible for noxious pollution from ships, but for invasive species it is prohibitively costly. One can search for the species and remove them when found; but unless it is optimal to search with such intensity that invasion risk is driven to zero, an external cost to trade still exists that would seem to call for some policy such as a tax (McAusland and Costello, 2002).

To an idealized social planner, this presents no great challenge—but an idealized social planner has little need to engage in international trade negotiation to begin with. The central accomplishment of those negotiations has been to rid participating countries of policies that were contrary to the interest of their own citizenry, but that emerge due to the fundamental asymmetry of trade politics—producers count more than consumers. Even in the best-functioning democracy, the benefits of trade barriers accrue to small groups of producers, while the costs are spread across a large group of consumers. It is easier to push the costs on diffuse consumers who have less incentive to form a group to fight for free trade. Producers use protectionism as a way to keep prices high to extract consumer surplus from consumers. This fundamental asymmetry of trade politics is mitigated by international rules that prohibit policies discriminating against foreign goods, but such rules are inappropriate for market failures in which it is the transport of the goods itself that does the harm.

Herein we present a straightforward incorporation of an invasive species externality in trade into the predominant model of the political economy of tariff formation (Grossman and Helpman 1994). The result is sharp—if countries are freely setting tariffs, the external damage is added to the tariff that would be chosen to redistribute income in the absence of the externality. While the simplicity of this argument is due in part to assumptions made for computational convenience, the result nonetheless serves to illustrate the interaction of public and private interest in the formation of a trade-environment policy. The result also indicates the impossibility of distinguishing legitimate public-goods protection from protectionism without full knowledge of the public-goods value.[1]

[1] In a companion piece, we discuss more complex policy options (see Margolis and Shogren 2004).

2. Background

We begin by providing background on free trade and invasive species management to help motivate our model. In the United States, regulators at the Animal and Plant Health Inspection Service (APHIS) routinely scrutinize new trade flows to determine the danger of known agricultural pathogens, refusing permission or requiring treatments if that danger is great. Similar policies towards invasive species—those that damage natural systems rather than agriculture—have been less common, but are becoming more so. It is unclear at present what it takes to prevent such policies from being overturned in trade disputes. Knowing when to expect this problem is of obvious value. To some extent, this is a legal question, a matter of how the trade laws will be read. But actual trade disputes result from both conflict between policies and trade agreement obligations and from trade-partner incentives to enforce those obligations. It would be beneficial to delineate the economic circumstances under which potential disputes can be expected to become actual disputes. As new trade agreements are reached, it is likely that dispute settlement procedures will be modified. Insight into the efficiency properties of alternative arrangements will be useful to help form negotiating positions resulting in agreements that make appropriate trade-offs between the gains from trade and losses due to invasive species.

U.S. regulators are limited by two trade institutions: the World Trade Organization (WTO) and the North American Free Trade Agreement (NAFTA). Each has its own rules, employing different evaluations of the costs and benefits of regulatory policies and the scientific basis for risk analysis. We will consider the current state of affairs for each in turn. The fundamental constraint the WTO legal framework imposes on national policymaking is the principle of national treatment specified in Article III, which requires importing countries to treat foreign goods the same way they treat "like" domestic goods. This is a straightforward requirement if imported goods are identical to something produced domestically, but usually something distinct exists about the imports that allows for varying interpretation about whether importers are suffering discrimination. There is therefore a set of "General Exceptions" (Article XX)—listed purposes for which measures may treat imports differently, unless they are deemed to be "arbitrary or unjustifiable discrimination between countries where the same conditions prevail" or "disguised restriction on international trade." These exceptions include measures "necessary to protect human, animal or plant life or health" (XX(b)) and those "relating to the conservation of exhaustible natural resources" (XX(g)).

These exceptions would appear to give importers little recourse if their product is banned with the express purpose of removing invasive species that threaten environmental quality or

food safety. By the time the General Agreement on Tariffs and Trade (GATT) was last renegotiated (the Uruguay Round 1986–1993), several disputes over the use of Article XX remained unresolved, and a consensus had emerged among trade negotiators that the existing legal structure was incapable of preventing trade disruption due to technical restrictions (Roberts 2000).

The result is embodied in two agreements that are among the founding documents of the WTO: the agreement on sanitary and phytosanitary (SPS) measures and the agreement on technical barriers to trade (TBT). The SPS agreement deals with more specific issues of human, animal, and plant health and lays out more detailed rules for coordinating policies. The TBT agreement establishes general principles for international coordination of product regulations across countries and sets criteria for imposing potentially discriminatory technical standards and regulations on imports.

In the SPS Agreement, the main discipline is the requirement that national policies be based on a risk assessment to the extent that they depart from internationally agreed-upon standards. This implies some scientific evidence must exist that a measure actually results in higher level of protection against some hazard than that afforded by international standards. There is no limit to the level of protection a nation may seek—a "zero risk" has been explicitly recognized as an acceptable goal. Nations may also adopt measures provisionally, while a risk assessment is being carried out.

What constitutes a risk assessment appears to vary depending on just what is at risk. According to Annex A of the agreement ("Definitions"), an assessment for food safety must be "the evaluation of the potential for adverse affects on human or animal health," while for the risk of disease or pest what is required is "the evaluation of the likelihood of entry, establishment or spread." This has been interpreted to mean that a measure to prevent the entry of disease or pest must include some estimate of the probability the disease or pest would become established in the importing country in the absence of the measure under challenge and another estimate that the probability is reduced in the presence of the measure. In contrast, for a food safety measure, it is sufficient to show that some actual danger exists (Pauwelyn 1999). In all cases, however, a risk assessment must be specific. A separate assessment is needed for each substance. And if a region within a country can be shown to be free of a pest, imports from that region must be allowed even if contamination of other regions precludes certification of the whole country.

The SPS Agreement also contains various provisions (i.e., Articles 5, 7, and 9) to encourage full disclosure of scientific information and to promote symmetry of information

among Members. Article 5 requires a Member to avoid arbitrary or unjustifiable distinctions in the levels of protection it deems appropriate, if such distinctions discriminate between imported and domestic products or create a disguised trade barrier. But it remains unclear what constitutes an unjustifiable distinction in levels of protection. It may be consistent with public preferences to tolerate different levels of protection against different health risks because some health outcomes are more socially salient than others (e.g., childhood diseases). Appropriate levels of protection may also vary due to the feasibility of mitigation measures or the magnitude of the societal benefits balanced against the risks.

The TBT Agreement applies to any rule requiring or prohibiting specific characteristics of a product, except for those that are covered by the SPS Agreement. In general, it is easier to defend a regulation if it can be brought under the TBT rather than the SPS. The transparency and nondiscrimination features of the two agreements are almost the same. The major difference is that an SPS measure must be backed by scientific evidence that it advances its goal, and the measure can be applied only to the extent necessary to achieve the proclaimed level of risk reduction. Measures subject to the TBT agreement do not, as a rule, have any equally verifiable purpose, so there is no equivalent requirement for scientific assessment (WTO 1998).

The TBT also covers measures related to packaging and labeling. As a rule, the TBT does not permit importing countries to place restrictions on how products are made, or "Process and Production Methods" (PPMs). Rather, standards must be written in terms of product characteristics that can be measured at the border. Based on position papers circulated by national delegations to the WTO, labeling requirements appear likely to emerge as an exception to the rule against PPM regulation, but this has not yet been codified in any formal agreement or, as far as we know, tested in case law.

The basic allocation of the burden of proof by WTO panels and appellate bodies dates from the earliest GATT panel practices (c. 1954). First, the exporting nation bears the burden of showing a violation of the national treatment principle—that is, of showing an imported good is like a domestically produced good and that it is being treated differently. Once this is established, the burden shifts to the importing nation to prove the challenged measure falls within the scope of Article XX. This requires the importing nation to show that the policy is aimed at one of the listed purposes, that it is necessary for the fulfillment of that purpose, and that it has not been applied arbitrarily or in such a manner as to constitute a disguised trade barrier (Pauwelyn 1998).

The burden of proof allocation has some distinct features in SPS cases, established in the dispute between the European Community (defendant) and the United States and Canada (complainants) over the use of growth hormones to raise beef cattle. There are still two phases, with the burden shifting from the exporting country in the first to the importing country in the second. But in SPS cases there is no difference between phases in what has to be proven. The complainant must make a prima facie case that the measure to which it objects is inconsistent with some provision of the SPS agreement; once that case is made, the defendant bears the burden to "counter or refute the claimed inconsistency" (Pauwelyn 1998).

The SPS requirement that there be "scientific" evidence appears to give official recognition to conventional confidence intervals as a standard of proof. Formally, panels commission independent experts to review the scientific evidence submitted in defense of an SPS measure and pronounce on whether there is or is not evidence that the measure protects the health of humans, other animals, or plants. Explicitly, they do not ask anything about how much protection is afforded—only whether scientists can verify that there is some. This is perhaps the key feature of the current system. It means that investment in larger scale studies should always be expected ex ante to increase the probability that a contested measure will be upheld. And it means that as knowledge accumulates, and we become more able to detect impurities and to ascribe ecosystem changes to biological invasion, we face a growing bias against trade.

The interpretation of the word "necessary" in the definitions of the general exceptions in GATT Article XX (i.e., a measure falls under the exception if "necessary to protect human, animal or plant life or health") also continues to evolve. If a measure were only deemed necessary when no other measure—regardless of cost—could achieve the proclaimed goal, the exception could be rendered meaningless. Early interpretation deemed a measure necessary if there was no less trade restrictive way to achieve the goal, but now even this is viewed as too narrow: what if there were a way that were a tiny bit less trade restrictive but imposed huge administrative costs? Current interpretation is somewhat loosely referred to as "a less-trade restrictive [approach], supplemented with a proportionality test" (WTO 2002). That is, if a measure is more trade restrictive than an alternative, it must have some compensating virtue of comparable magnitude.

As compared with the WTO, NAFTA allows national governments more latitude over their technical standards and SPS measures. This is made clear by three features of the agreement. First, the burden of proof in arbitration over SPS or TBT measures is assigned to the plaintiff, or the party challenging the law or regulation (Articles 723.6 and 914.4). Second, arbitration cases may be heard either by a NAFTA or a GATT panel, at the option of the

defending party. Third, NAFTA does not contain an explicit least-trade-restrictive requirement for those measures that would fall under the TBT Agreement, which does include such a requirement.

Now consider the case of NAFTA, which created the Commission for Environmental Cooperation (CEC) between Canada, Mexico, and the United States. The Statement of Administrative Action strengthens regulators under NAFTA in two additional ways. First, it explicitly states that the requirement that an SPS measure be "necessary" to achieve its goals is not to be interpreted as meaning it must be the least trade restrictive option. Second, the scientific basis for setting levels of allowable risk in SPS measures is determined by the regulating authority (the defendant), not by a dispute settlement panel (Hufbauer et al. 2000).

One well-known element of NAFTA runs counter to this tendency. Chapter 11 gives firms from one nation the right to initiate disputes against the governments of other nations if the firm claims that an investment it made in the other nation has been expropriated. This investor-state dispute mechanism has no counterpart in the WTO, where an aggrieved private party must convince its government to file the dispute on its behalf. Several investors have filed claims with NAFTA arbitrators, asserting that regulatory actions that reduced the value of their investments constituted a form of expropriation. Mexico has lost one of these cases and partially lost its initial appeal to the Supreme Court of British Columbia. Another round of appeals may still reverse this decision, but if it stands, it will constitute a distinct and potentially significant constraint on regulatory design.

Based on their concern about transboundary invasions, the Commission for Environmental Cooperation (CEC, 2001) recently recommended five priority areas for invasive species management within NAFTA. These recommendations were put forth nearly a decade after NAFTA was negotiated, and the priority areas seem rather obvious today. Their explicit declaration by the CEC, however, makes clear the mounting pressure to address invasives in on-going NAFTA discussions. First, the CEC requested more science on the identification of invasives and their pathways due to trade; second, they asked for a formal centralized network to collect and disseminate information about invasives; third, they requested the development and distribution of tools to raise awareness and empower decisionmakers interested in control invasives; fourth, they want to create a regional directory of legal institutions for all three North American countries; and finally, the CEC agreed to identify tools to provide economic incentives to engage industrial and commercial sectors. This last point clearly recognizes the public need to engage the well-organized private industrial groups that lobby for tighter or looser trade

restrictions within NAFTA. The open question we address now is how the private lobbying efforts affect the public policy to control invasive species within international trade.

3. A Model

We consider now our basic model, which extends Grossman and Helpman's (1994) analytical framework that examines the interaction of interest groups and a government that cares about general welfare. Their basic model has successfully predicted the structure of protection in the United States (Gawande 1997), and Turkey (Mitra, Thomakos et al. 2002). Our extension is intended to add the minimal complexity needed to incorporate an externality in trade to make as clear as possible what difference this element implies.

The following process determines lobbyists' contributions to the government. Before the government makes its decision, each organized lobby draws up a *contribution schedule*. This schedule is a perfectly binding agreement that commits the lobbyist to contribute a specific amount for every policy choice the government might make. Since we assume no uncertainty exists about the price impact of policies, a schedule of contributions as a function of policies is equivalent to a function of outcomes—prices (**p**) and external damage—which is simpler to work with. Also, since we assume a tariff is the only tool to address the trade externality, the external damage level is fully determined by the import levels, which are fully determined by **p.** This implies we can write the contribution schedule offered by an environmental lobby as $C(\mathbf{p})$. For simplicity, assume no environmental lobby exists.[2] As in the GH model, the lobbies are the private owners of certain specialized factors of production, the rents to which depend on prices alone.

Government cares both about general welfare and about campaign contributions.[3] A government objective function arises from the desire of political parties to remain in power. Consider incumbents who see their reelection probability as greater if society is better off, and also as greater if they can spend more on elections. Some may also want social welfare high for altruistic or idiosyncratic reasons—but this addition does not make a difference to the theory.

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[2] See Aidt (1998) for a discussion of how environmental lobbies fit into this framework.

[3] The basic GH model has successfully predicted the structure of protection in the United States (see Goldberg and Maggi 1999; Gawand, 1997) and Turkey (see Mitra et al. 2002).

What is central to the model is that the relative weight the incumbents place on social welfare versus campaign contributions is constant, regardless of the origin of contributions or whether increments to social welfare take the form of environmental improvement, a rise in consumer surplus, or a rise in government revenue.

We capture this intuition in a government-objective function

$$G = \sum_{j \in L} C_j(\mathbf{p}) + aW(\mathbf{p}, \boldsymbol{\delta} \cdot \mathbf{m}) \qquad (1)$$

where **p** is the price vector; **δ** is a vector of constant marginal external damage per unit import; **m** is the import vector; C_j is the contribution to incumbents given by the j^{th} lobby; a is the exogenous weighting of consumer welfare; and L is the set of factors the owners of which have successfully organized, also exogenous.[4] The government objective function (1) differs from GH only by the inclusion of a damage term in the welfare function.

Adding the environmental externality in trade requires additional assumptions be added on the distribution of the externality across citizens. The most reasonable starting point is to assume this distribution is equal. For simplicity, assume also the marginal external damage done by a unit of import is a vector of constants **δ**, the i^{th} element of which is the damage done by import of a unit of good i. If good i is exported $\delta_i=0$, in the case of a consumption-related externality. The welfare of the membership is

$$W_i \equiv \ell_i + \pi_i(p_i) + \alpha_i N\left[r(\mathbf{p}) + s(\mathbf{p})\right] - \alpha_i \boldsymbol{\delta} \cdot \mathbf{m}(\mathbf{p}) \qquad (2)$$

where ℓ_i is the total labor income of the group, α_i is the fraction of the population in lobby i, $r(\mathbf{p})$ the *per capita* revenue from tariffs (net of payment for export subsidies), $s(\mathbf{p})$ the *per capita* consumer surplus and $\mathbf{m}(\mathbf{p})$ the vector of total imports.

Social welfare is

$$W(\mathbf{p}) = \ell + \sum_{i=1}^{n} \pi_i(p_i) + N\left[r(\mathbf{p}) + s(\mathbf{p})\right] - \boldsymbol{\delta} \bullet \mathbf{m}(\mathbf{p}) \qquad . \quad (3)$$

[4] Assumptions of exogeneity and functional form not explicitly discussed are taken from Grossman and Helpman.

The sequence of events is (i) lobbies select contribution schedules $C(\mathbf{p})$; and (ii) the government, observing those contribution schedules, sets $\boldsymbol{\tau}$ to maximize G. This structure is in the class of problems known as *menu auctions*, the general properties of which were examined in (Bernheim and Whinston 1986). Two properties matter for our context. First, lobbies are likely to exploit *truthful strategies*: that is, the contribution schedule is such that the lobby is indifferent as to which policy ultimately gets chosen among those for which it is willing to make some positive contribution. Equivalently, a truthful contribution schedule for lobby i is equal to the gross welfare function W^i minus some constant. Bernheim and Whinston show that among the possible best responses of any player in any menu auction game, there exists a truthful strategy. If any communication among players is possible, equilibria composed of truthful strategies are, for practical purposes, the only stable ones. Roughly speaking, nontruthful strategies can be undermined by coalitions, even when there is no mechanism available to enforce agreements. For this reason, we consider only truthful strategies.

The second feature is that the Nash equilibrium in a menu auction must maximize the joint payoff of the auctioneer (i.e., government) and each bidder (i.e., lobby) given the contribution schedules of all other bidders. The parameters underlying the bid functions are common knowledge. This means C_j^e cannot be part of a Nash equilibrium with prices $\mathbf{p}^e$ unless it maximizes

$$W_j\left(\mathbf{p},\Delta\right)-C_j^e\left(\mathbf{p}\right)+G \tag{4}$$

over all $\mathbf{p}$.

Assuming contribution schedules are differentiable, combine the first order condition for maximization of expression (4) with that for maximization of G and sum over the organized lobbies to get

$$\sum_{i\in L}\frac{\partial}{\partial p_i}W_i\left(\mathbf{p},\Delta\right)+a\frac{\partial}{\partial p_i}W\left(\mathbf{p},\Delta\right)=0 \quad \forall i \tag{5}$$

Now invoke several assumptions (see the Appendix for details) used by GH to get expressions for the specific factor rents, consumer surplus, supply $y_j\left(p_j\right)$, demand, and imports $m_j\left(p_j\right)$. Taking the derivative of expression (2) and summing across all the organized lobbies shows the first term in (5) to be

$$\sum_{i\in L}\frac{\partial W_i}{\partial p_j}=\left(I_j-\alpha_L\right)y_j\left(p_j\right)+\alpha_L\left(\tau_j-\delta_j\right)m_j'\left(p_j\right) \tag{6}$$

where I_j=1 if the industry has a lobby $\left(i \in L\right)$ and zero otherwise. Taking the derivative of expression (3) gives

$$\frac{\partial W}{\partial p_j} = \left(\tau_j - \delta_j\right) m_j'\left(p_j\right) \tag{7}$$

Substituting (6) and (7) into (5) gives the equilibrium per unit tariff,

$$\tau_j = \delta_j + \frac{I_j - \alpha_L}{a + \alpha_L} \frac{y_j\left(p_j\right)}{\left|m_j'\left(p_j\right)\right|} \tag{8}$$

We see from expression (8) that the tariff always exceeds the marginal damage of the import. The last term on the right side of (8) is the same as in the GH model:[5] *the expression for the equilibrium tariff if there is no externality is the difference between the equilibrium and optimal tariff when there is an externality.* This generalizes the GH idea—political contributions induce a gap between equilibrium and optimum. This gap is a logical measure of disguised protectionism.

Perhaps the most important feature of (8) is that the two components of the tariff—disguised protectionism and internalization of invasives damage—cannot be distinguished without knowledge of either the social damage vector $\boldsymbol{\delta}$ or the weight the government places on public welfare a. In this context, then, there is no way to design trade disciplines that will reduce disguised protectionism without nations giving international bodies the right to decide how much value should be placed on the public goods endangered by invasive species. It is perhaps unnecessary to point out that no such surrender of national sovereignty is contemplated in the current round of trade talks.

4. Concluding remarks

Economists argue that countries should encourage free trade because it allows countries to specialize in producing those goods and services in which they have a comparative advantage. Trade opens each economy to import goods produced by less expensive means of production

[5] GH present the expression for *ad valorem* tariffs, rather than per unit, so there is no expression identical to the last term **Error! Reference source not found.** in their paper.

given basic differences in endowments. Provided property rights are well-defined and enforced, free trade is argued to generate more overall welfare in both nations. Invasive species, however, are a counterexample against unrestricted free trade. Free trade with exotic hitchhikers might not be good for the environment or for the people who depend on the related ecosystem services (e.g., zebra mussels in the Great Lakes).

But public policies to control these invasive species are not immune from political pressure from private interest groups. Herein we explore how well-organized interest groups can affect a public decisionmaker's choice of tariff levels to reduce the risk of invasive species. The interest group offers up political contributions to an incumbent interested in both the general welfare of the public and its own chances of reelection. We find that private political contributions cause the regulator to select a tariff level that exceeds the socially optimal level. Free trade is too constrained. The invasive-species tariff is set higher than it would be if government were independent of rent-seeking contributors. This gap is *disguised protectionism* created by the existence of invasive species. Good intentions aimed at reducing risks to native ecosystems from exotic invaders can be leveraged into protectionist policies. The degree to which we should be concerned about this protection is the next step in this line of research. Measuring empirically the level to which disguised protectionism exists in either the WTO or NAFTA seems most worthwhile.

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Appendix

The following assumptions are used by us and by GH to simplify calculation of demand and supply slopes, bid functions, and so on. There is no specific factor used in production of the numeraire good, which is produced by labor alone. All production occurs under constant returns to scale, all world prices are exogenous, and it is impossible to alter the world price of the numeraire. This means it is also impossible to alter the nominal wage, which by suitable choice of units is set to unity. Constant returns and a constant wage means the returns to specific factor i depend only on the price of output i; write this as $\pi_i(p_i)$ No citizen owns any of more than one specific factor, and within the group of factor owners all are identical. Utility is additively separable with strictly concave subutility functions u_i, and (without loss of generality) the subutility function for the numeraire is linear with unit coefficient

$$U = x_0 + \sum_{i=i}^{n} u_i(x_i) - \boldsymbol{\delta} \cdot \mathbf{m}(\mathbf{p})$$

where x_i is consumption of good i. This assumption adds structure to demand curves and the consumer surplus expression. Defining $d_i \equiv 1/u_i'(x_i)$, *per capita* demand is

$$x_i = d_i(p_i) \quad i \in \{1, 2, \ldots n\}$$

$$x_0 = E - \sum_{i=1}^{n} p_i d_i(p_i)$$

and consumer surplus *per capita* is

$$s(\mathbf{p}) = \sum_{i=1}^{n} u_i(d_i(p_i)) - \sum_{i=1}^{n} p_i d_i(p_i) .$$

From a tariff vector $\boldsymbol{\tau}$ (which can include negative elements to represent export subsidies) the total revenue *per capita* is

$$r(\mathbf{p}) = \boldsymbol{\tau} \cdot \mathbf{m}(\mathbf{p}) / N .$$

Finally, given the envelope theorem, domestic output of good i is

$$y_i(p_i) = \pi_i'(p_i),$$

and imports can be written

$$\mathbf{m} = N\mathbf{d}(\mathbf{p}) - \mathbf{y}(\mathbf{p}) .$$