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Exports and Externalities: the other side of trade and ecological risk

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Abstract

This paper develops a general equilibrium model to measure welfare effects of taxes for correcting environmental externalities caused by domestic trade, focusing on externalities that arise through exports. Externalities from exports come from a number of sources. Domestically owned ships, planes, and automobiles can become contaminated while visiting other regions and bring unwanted pests home, and species can be introduced by contaminated visitors that enter a region to consume goods and services. The paper combines insights from the public finance literature on corrective environmental taxes and trade literature on domestically provided services. We find that past methods for measuring welfare effects are inadequate for a wide range of externalities and show the most widely used corrective mechanism, taxes on the sector imposing the environmental externality, may often do more harm than good. The motivation for this

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paper is the expansion of invasive species' ranges within the United States. We apply our analytical model to the specific example of quagga and zebra mussel (*Dreissena polymorpha* and *Dreissena rostiformis bugenis*) invasion into the U.S Pacific Northwest.

Keywords: environmental regulation, tax interactions, invasive species, environment and trade

JEL Codes: Q20, Q26, Q27, Q56, Q57, F18

1 Introduction

The trade and environment literature has recently focused on externalities due to contact with trade partners, particularly with regard to import goods and invasive species (see for example Perrings et al. [32], McAusland and Costello [24], Margolis *et al.* [22], and Knowler and Barbier [19]). As these authors have pointed out, trade is much like any other risky behavior in which humankind partakes. Agents must balance risk of contamination with enhanced opportunities from multiple trade partners. Well informed agents can optimally manage this risk by choosing private or public methods of protection and insurance [34]. Work along these lines has focused on externalities introduced through imports (particularly with regard to invasive species), and largely ignored the contact with trade partners through exports and trade in domestically provided services. Externalities from exports come from a number of sources. Domestically owned ships, planes, and automobiles can become contaminated while visiting other regions and bring unwanted pests home, and species can be introduced by contaminated visitors that enter a region to consume goods and services. Following the the trade literature [10, 25, 37, 8, 9], consumption of goods and services by nonresidents are modeled as exports, as money flows from outside the region to local firms and households.[1]

Differentiating between import- and export-related externalities determines the ability of agents to manage the associated risk. Consumption of imports can be taxed in a way that internalizes cost of environmental damages within the regional economy. Exports offer no such possibility. We show that taxes on the sector imposing the environmental externality may do more harm than good when exports are the culprit even though they successfully reduce exposure to risk; public methods of protection may be counterproductive. Our results contrast, for example, McAusland and Costello [24] who find that the optimal tax on imports of potentially invasive species is generally positive.[2] Because exports are produced with local factors of production, levying a tax could cause declines in domestic production, and thus local income, large enough to offset any welfare gains from correcting the environmental problem. We examine this problem in a general equilibrium model with a preexisting labor tax and present new welfare effects necessary for studying a wide range of externalities beyond those found in the public finance literature on environmental regulation and tax interactions.[3][4]

The motivation for this paper is the domestic spread of invasive species. It is the first paper to focus on human mediated domestic spread despite growing concern among policy makers and ecologists about within-country dispersal. Of *100 of the World's Worst*

[1]The tourism industry, for example, can be described by purchases of domestic goods and services by nonresidents. Large hospitals often serve patients from outside of the region, and recipients of outsourced work are essentially in the business of exporting factors of production.

[2]In a model with taxes and inspections, they find optimal tariffs are non-negative, and equal to zero if and only if inspection is costless and detection is perfect.

[3]There is a well-established literature on welfare effects of environmental taxes, including Bovenberg and de Mooij [5], Bovenberg and van der Ploeg [6], Parry [29], Goulder [14], Goulder *et al.* [15], Fullerton and Metcalf [13], and Williams [40].

[4]Recent findings of a fish virus (*viral hemorrhagic septicemia*) havr restricted interstate transport of live bait in the Great Lakes area. Other examples of externalities from exported services and visitor consumption are automobile exhaust [31], diver impact of coral reefs [17], and pollution tied to sporting events [7]. While these externalities are well know, little has been said about the welfare effects of policies to correct these externalities.

Invasive Alien Species listed in the Global Invasive Species Database [21], 86 species have been introduced into the United States or are increasing their range within the United States, seven species are indigenous or non-threatening to other areas of the U.S., and seven have not been introduced.[5] These species are often introduced near major ports of entry as 'hitchhikers' on international transporters, and following introduction and colonization, hitchhiking on domestic transportation expands the species' range. A species is deemed invasive, as opposed to simply nonnative, if it causes economic or ecological damages in the ecosystems where it is newly established.

We apply our model to the threat of invasion by zebra and quagga mussels (*Dreissena polymorpha* and *Dreissena rostiformis bugenis*, hereafter collectively referred to as dreissenids) into the Columbia River Basin. Following an invasion, dreissenids cover surfaces and clog intake pipes for industries dependent on water, requiring costly installation of mitigation equipment and additional personnel to monitor and control the effects. They are also prolific filter feeders, causing ecosystem-wide effects in the bodies of water they invade. They compete with native mussels [33] and have been linked to declines in catches and conditions of sport fish [16, 23, 26, 36] and lost recreational opportunities [38].

The Columbia River Basin is an ideal case study for several reasons. First, the basin's location in the Pacific Northwest has protected it from introduction from non-U.S. sources. Dreissenids arrived in the U.S. through shipping channels connecting the East Coast and Europe. The only realistic vectors of introduction into the basin are of U.S. origin. Second, the Rocky Mountains and the Continental Divide have provided barriers of natural introduction. No body of water in the Columbia River Basin is directly connected to any currently invaded body of water making within-stream dispersal impossible. Introduction must occur through overland transport, of which trailerd boats are the most likely vector.

[5]These figures include introduction into and between Hawaii and U.S. island territories. Included in the seven not currently present are two seaweeds, a seastar, and a comb jelly.

Such boats can be easily inspected at launch sites and checkpoints along the roadways. Third, a dreissenid invasion is expected to impact recreational fishing in the Columbia River Basin, a regionally significant economic activity. Nearly 4 million recreational fishing licenses, permits, and stamps were sold to anglers in the Columbia River Basin in 2007, over 700,000 of which were to non-residents [12]. Two million individuals spent $50 million on licenses, and according to the American Sportfishing Association [1], added $3 billion to the local economies. Finally, we have data on the suitability of basin waters as dreissenid habitat and on boat movement between these bodies of water and infested regions of the U.S. [35, 11, 3, 4, 39]. Bossenbroek et al. [4] estimate the overland boat traffic potentially infected with dreissenid mussels traveling to the Columbia River Basin in a given year. The mere threat of invasion these boats carry has already caused impacts in the region.

In what follows the analytical model is developed and analytical welfare effects of an environmental tax for this class of externality are derived in the fashion of Bovenberg and de Mooij [5], Fullerton and Metcalf [13], and Williams [40]. The method is implemented in a regional computable general equilibrium (CGE) model for the Columbia River Basin and lost welfare associated with uncertainty and welfare effects of corrective taxes are calculated. A brief discussion concludes.

2 Analytical Model

In a general equilibrium setting a regional firm provides goods to two utility maximizing consumers, a resident and a visiting nonresident. There is some chance of introduction of a nonnative species that depends on the level of sales to the visiting consumer. This uncertainty enters the model exogenously through the non-resident, as they are unaware of its presence, and is assumed to only be of direct consequence to the expected profit maximizing firm. If an invasion occurs, the firm must adopt a less efficient production technology. A government agent levies a tax on sales to nonresident consumers in order to reduce the probability of an invasion. These tax revenues are used to lower a preexisting labor tax. Price for the consumption good and wages adjust until the goods and labor markets clear, ensuring general equilibrium. The assumptions of the analytical model match the behavioral specifications of the computational model presented in section four.

2.1 Assumptions

A price-taking domestic firm produces a good using only labor. The product is sold to a resident and visiting nonresident consumer. The firm cannot distinguish between the resident and nonresident consumers and charges a single price in the marketplace. The probability of invasion $\gamma(X_{NR})$ increases with the total amount of goods (X_{NR}) sold to the nonresident. The firm does not account for this effect in its optimization problem, perhaps because it believes its own contribution to the problem is miniscule.[6] A successful invasion degrades environmental quality, forcing the firm to use a less efficient production technology. Faced with this uncertainty, the firm chooses labor to maximize expected profits,

$$\pi = P[\gamma F(L, Q^I) + (1-\gamma)F(L, Q^N)] - wL \tag{1}$$

where $F(L, Q)$ is the production function, L is the amount of labor input, Q is environmental quality, P is the price of the good, and w is the wage rate. Superscripts denote invaded (I) and non-invaded (N) states of the environment. Total production must be greater than or equal to total consumption (X), and because the firm cannot distinguish between resident (R) and nonresident (NR) consumers, $F(L, Q) \leq X = X_R + X_{NR}$.

The production process is constant returns to scale, $X = L\phi(Q)$, and production units are normalized so $\phi(Q^N) = 1$ without invasion and $\phi(Q^I) = \phi \leq 1$ with invasion. We also

[6]This assumption also allows for modeling consistency with Williams [40] and similar papers.

normalize the price of the domestically produced consumption good to unity. The expected profits of the firm are

$$\pi = \gamma\phi L + (1-\gamma)L - wL \tag{2}$$

A zero profit condition implies that labor earns its expected marginal product

$$w = \gamma\phi + (1-\gamma) \tag{3}$$

The firm's optimization problem defines the supply of the good and demand for labor as a function of the real wage, $X = X^s(w)$ and $L = L^d(w)$.

A representative domestic household maximizes utility by consuming the domestic good (X_R) and enjoying leisure (l). The household is endowed with T units of time that are divided between labor (L) and leisure. The household receives income from labor, any firm profits, and government transfers (G). The household makes its consumption decision knowing the wage offered by the firm and the price of the consumption good. Uncertainty, therefore, does not affect the consumption decision of the household except for an indirect effect on wages as shown in the firm's decision problem. Household income is used to purchase the consumption good and to pay the tax on labor at rate τ_L. The household has utility function

$$U(X_R, l) \tag{4}$$

and faces budget and time constraints

$$wL(1-\tau_L) + \pi + G = X_R \tag{5}$$

$$L + l = T \tag{6}$$

We assume the utility function is continuous and quasi-concave. Letting λ be the marginal utility of wealth, the first order conditions for the household with respect to X_R and l are

$$U_X = \lambda; \quad U_l = \lambda(1 - \tau_L)w \tag{7}$$

The first order conditions implicitly define Marshallian demand functions for the consumption good $X_R(w, \tau_L, \pi, G)$ and the supply of labor $L^s(w, \tau_L, \pi, G)$.

A representative nonresident gets utility from consuming the local good in amount X_{NR}. The good is immobile so consumption must take place within the region of production.[7] The nonresident also consumes a similar product in his home region (X_F) with price P_F that is an imperfect substitute for the local good. In order to purchase the local good, the visiting consumer must pay the price for the domestic good plus an additional tax (τ_{NR}). Since firms cannot distinguish between the consumers, we assume the tax on the visitor is in the form of an entry fee or a surcharge on nonresidents charged and collected by the government agent (e.g., toll booth at the state border or an out-of-state fishing license). The visitor has utility function

$$V(X_{NR}, X_F) \tag{8}$$

and faces budget constraint

$$M = P(1 + \tau_{NR})X_{NR} + P_F X_F \tag{9}$$

The visitor's utility function is assumed to be continuous and quasi-concave with income M exogenous. Letting μ be the marginal utility of the nonresident's wealth, the first order

[7] Examples of such goods include locally provided services like hospital services, hotel lodging, mechanic work, haircuts, and guided fishing trips.

conditions for the nonresident with respect to the domestic and foreign goods are

$$V_{X_{NR}} = \mu(1 + \tau_{NR}); \quad V_{X_F} = \mu P_F \tag{10}$$

The first order conditions implicitly define a Marshallian demand function for nonresident consumption $X_{NR}(\tau_{NR}, P_F)$, which we assume to be a normal good.

A government agent initially only taxes labor income and redistributes the revenues back to the resident household in a lump sum amount G. Given a chance nonnative species are introduced, the government levies an additional tax on consumption of the visiting nonresident, hereafter referred to as the environmental tax. Revenues from the environmental tax are used to lower the labor tax. Total government revenues, and thus total government transfers to the resident, are fixed at G regardless of the tax mix. The government budget constraint is

$$G = \tau_L wL + \tau_{NR} X_{XR} \tag{11}$$

2.2 Equilibrium

The maintained assumption is that all choices are made ex-ante to an invasion, but the threat of invasion persists. General equilibrium is achieved through adjustment of the price and wage until supply of the good equals the sum of demand from the resident household and nonresident visitor, demand for labor equals supply of labor, and the government balances its budget.

Given the derived demand and supply functions, the goods market clears when price adjusts so $X = X_R + X_{NR}$, and the wage adjusts until the labor market clears, $L^d = L^s$. With neither a labor tax nor threat of invasion, the resident's equilibrium marginal rate of substitution of leisure for consumption would equal the marginal revenue product of labor to the firm. Both the labor tax and the threat of invasion, however, cause distortions in the labor market. With a labor tax the resident withholds labor that would have otherwise gone on the market, causing a higher wage rate than without the distortion. The threat of invasion counters this effect by lowering the expected productivity of labor, causing lower wages than would otherwise exist.

All tax revenues are redistributed to the resident. This guarantees the government maintains a balanced budget and satisfies the final equilibrium requirement. Combining the market clearing conditions in the goods and labor market provides an aggregate resource constraint for the economy. In an uninvaded scenario L units of labor are required to produce X, allowing

$$L^d = X_R^d + X_{NR}^d \tag{12}$$

The firm cannot distinguish between resident and nonresident consumers, so the resource constraint also defines the economy's transformation function, with a constant elasticity of transformation of one between domestic and foreign consumption. A one unit change in demand for the good, regardless of which consumer changes its demand, causes a one unit change in labor demanded.

3 Welfare Effects

Levying the environmental tax decreases the visitor's demand for the good and lowers the probability of an invasion. Because risk of production inefficiencies fall the firm demands more labor, produces more output, and wages rise. Taxing the visitor's consumption also allows the government to lower the tax on labor, releasing more labor into the marketplace. This further raises income to the resident. Increasing the price to the foreign consumer, however, may cause the aggregate quantity demanded to fall. If this happens, labor demanded will fall accordingly and household income may fall. The net change in household welfare depends on the change in output and the demand for labor relative to the change in the wage rate. All else equal, a lower probability of invasion increases the real wage and causes unambiguous welfare gains. The following analysis concerns itself with the inherent tradeoffs involved with using a tax to achieve this means and the interaction affects with a preexisting tax.

A large literature exists on potential gains from an environmental tax that may exist beyond correcting the externality, often known as the 'double dividend' hypothesis. Oates [28] reviews this literature and discusses the existence of the double dividend. Although we follow these basic methods to assess welfare effects, direct comparisons are not clear given the cause of externalities in this literature. In previous studies, externalities generally arise from resident consumption with no mention of nonresidents. For example, the tax-interaction effect, the ability of an environmental tax to raise the price of that good in relation to leisure and compound the distortion in the labor market, does not exist in our model since the price of the dirty good only rises for nonresidents. In addition, in our primary welfare effect, or Pigouvian effect, there are both positive and negative elements: nonresident consumption increases the probability of invasion (negative externality) and brings income to the resident household (positive externality).[8] We, therefore, refer to the *negative externality in the primary welfare effect* and the *positive externality in the primary welfare effect* in our discussion of welfare changes. Direct comparisons can be made between our model and those in previous studies for the revenue recycling effect [14], which describes the ability of an environmental tax to raise public revenues and decrease other distortionary taxes.

Our main result for the net welfare effect from the environmental tax is summarized

[8]Goulder *et al.* [15] has a model with revenue recycling, tax-interaction, and primary welfare effects, though they only consider welfare effect tied to negative externalities.

by equation (13) and derived in the appendix.

$$\frac{dU}{\lambda d\tau_{NR}} = -wL\frac{d\tau_L}{d\tau_{NR}} - \tau_L L\frac{dw}{d\tau_{NR}} - X_{NR}(\eta+1) + \gamma(1-\phi)\frac{dL}{d\tau_{NR}} \tag{13}$$

$\eta = \frac{dX_{NR}}{d(1+\tau_{NR})}\frac{1+\tau_{NR}}{X_{NR}}$ is the price elasticity for visitor demand.

Equation (13) shows the two main components of the welfare effect of the tax, termed the revenue recycling effect and the primary welfare effect. Welfare changes for the resident are determined by the relative sizes of changes in labor and nonresident consumption through these effects and are, *a priori*, ambiguous. The revenue recycling effect is captured by the first two terms on the right side of (13) and represent changes in labor tax payments following introduction of the environmental tax. Levying the tax on the nonresident consumer allows the government to lower the tax on labor. $\frac{d\tau_L}{d\tau_{NR}} < 0$ is the efficiency of the tax tradeoff, and $-wL\frac{d\tau_L}{d\tau_{NR}} > 0$ is the amount of labor tax savings, which allows resident income to rise. The magnitude of this part of the revenue recycling effect depends on the revenue raising efficiency of the two taxes and labor income.

Reducing nonresident consumption lowers the probability of invasion and increases the expected productivity of labor. Higher wages require the resident household to pay more in labor taxes, given by $-\tau_L L\frac{dw}{d\tau_{NR}} < 0$. The magnitude of this part depends on the ability of the tax to influence the probability of invasion, the expected productivity of labor, and the equilibrium wage. Because adjustment of the labor tax is the primary means of compensating the resident for the externality, we assume that the sum of these two terms, and thus the revenue recycling effect, is positive.[9]

The primary welfare effect (third and fourth terms on right side of (13)) deviates from other studies and is indeterminate due to the countervailing positive and negative external-

[9]The rise in labor productivity could be considered part of the benefit-side tax-interaction effect in Williams [40], but as the larger effect involves the benefit from reduced taxes, we consider the total change in labor tax payments the revenue recycling effect.

ities. Note that w depends on the probability of invasion γ, and the probability of invasion depends on nonresident demand X_{NR}. The tax decreases risk of invasion according to

$$\frac{d\gamma(X_{NR})}{d\tau_{NR}} = \gamma\prime(X_{NR})\frac{dX_{NR}}{d\tau_{NR}} \leq 0 \tag{14}$$

which affects the equilibrium wage

$$\frac{dw}{d\tau_{NR}} = \gamma\prime(X_{NR})\frac{dX_{NR}}{d\tau_{NR}}(\phi - 1) \geq 0 \tag{15}$$

(15) shows the relationship between the elasticity of nonresident demand and the elasticity of wage with respect to the environmental tax. Defining $\xi = \frac{dw}{d(1+\tau_{NR})}\frac{1+\tau_{NR}}{w}$, we can write $\eta = \xi w/(X_{NR}(\phi - 1)\gamma\prime(X_{NR})) \leq 0$.

The sign of $-X_{NR}(1+\eta)$ depends on the visiting consumer's elasticity of demand. This term reflects the ability to correct the externality by leveraging nonresident consumption. If nonresident demand is inelastic, $\mid \eta \mid < 1$, the third term will be negative and the marginal effect of the tax becomes more negative with higher levels of nonresident consumption. If nonresident demand is elastic, $\mid \eta \mid > 1$, taxes cause large changes in nonresident demand, and welfare gains from the primary welfare effect are leveraged by nonresident consumption.

The sign of the last expression $\gamma(1-\phi)\frac{dL}{d\tau_{NR}}$ depends on the sign of dL, as $\gamma(1-\phi) > 0$ is the share of the wage influenced by the threat of an invasion. If the elasticity of demand is highly elastic, the two terms in the primary welfare effect work in opposition. Small increases in the tax cause large reductions in X_{NR} and large reductions in labor demand dL, leaving the overall direction of the primary welfare effect ambiguous without further restrictions. However, if demand is only slightly elastic, X_{NR} is not sensitive to changes in the tax and dL is small, and the primary welfare effect is negative.

The sum of all effects hinges on a key economic behavioral parameter, the elasticity of nonresident demand, and its relationship with a key parameter at the intersection of the economic and ecological processes, the probability of invasion. If demand is highly elastic, the environmental tax is not likely an effective way to raise government revenues; we would expect $-wL\frac{d\tau_L}{d\tau_{NR}}$ to be close to zero. The tax, however, is an effective tool to correct the externality and raise the real wage. A higher wage also leads to higher labor tax payments by the resident; $-\tau_L L\frac{dw}{d\tau_{NR}}$ would rise. If $-wL\frac{d\tau_L}{d\tau_{NR}}$ tends to zero in the limit, total welfare increases if and only if

$$-X_{NR}(1+\eta) > \tau_L L\frac{dw}{d\tau_{NR}} - \gamma(1-\phi)\frac{dL}{d\tau_{NR}} \tag{16}$$

The inequality in (16) will only be satisfied if small changes in the tax rate have little to no effect on wages and labor. However, the opposite was assumed to derive (16), making it unlikely. For the case of highly elastic nonresident demand we therefore expect an environmental tax to lead to a welfare loss for the resident.

For the opposite case of very inelastic nonresident demand, changes in labor and wage are small. Approximating $-\tau_L L\frac{dw}{d\tau_{NR}}$ and $\gamma(1-\phi)\frac{dL}{d\tau_{NR}}$ at zero in the limit, resident welfare will rise (fall) if the sum of $-X_{NR}(1+\eta) < 0$ and $-wL\frac{d\tau_L}{d\tau_{NR}} > 0$ is positive (negative). In this case, a corrective environmental tax increases resident welfare by generating enough government revenue to lower labor taxes.

In summary, with highly elastic demand, taxing nonresident consumption causes large drops in labor demand. Income to the resident falls more than gains from higher wages and labor tax savings. If demand is inelastic, taxing the visiting consumer hardly reduces the probability of invasion, but labor income remains relatively unchanged. The resident household benefits through the reduction in labor taxes. An environmental tax can lead to welfare gains to the resident only if demand is inelastic, but not by correcting the externality. Should conditions exist to correct the externality (demand is elastic), lost labor demand hurts the resident household more than extra income from higher wages and lower taxes.

4 Columbia River Basin as an Example

In the spirit of Goulder [14] and Goulder *et al.* [15], we apply the analytical model to a CGE model of a potential dreissenid invasion into the Columbia River Basin and the effects of a tax on nonresident recreational anglers aimed at preventing this invasion. The application implements the analytical model and provides numerical results that are the net of the indeterminate analytical results, explicitly modeling the probability of invasion, expanding the analysis to an economy with nine producing sectors, nine representative households, state and federal government agents that levy taxes on labor, and expanding our treatment of the production process to include capital and intermediate inputs. Other than the added complexity, all model and agent behavioral assumptions are identical to those of the analytical model. In the Columbia River Basin context, nonresident refers to all consumers living outside of the basin, and trade is defined as all economic exchange with U.S. residents living outside the basin and consumers living outside of the U.S. Hicksian equivalent variations are used to measure welfare changes.

Visitors enter the Columbia River Basin to 'consume' fishing and boating experiences. To the extent that one fishing location is not a perfect substitute for another, the experience must be consumed within the basin. Production of the fishing experience (providing fishing licenses, hotels, restaurants, etc.) uses Columbia River Basin factors of production and is an important source of regional income. Visiting anglers also bring risk of dreissenid invasion to the Columbia River Basin, mainly through unintentional transport of dreissenids aboard trailored boats. Because invasion caused by any one boater is likely to lead to widespread damages, we model the probability of invasion as a weak-link public good as in Perrings *et al.* [32] and Horan *et al.*[18]. We assume the habitat is conducive to host the invasive species [11] and all visitors' actions are exactly alike in that they carry the same probability of invasion (q).

The probability that successful introduction occurs by any visiting boater is

$$\gamma(n) = Pr(Z \geq 1) = 1 - \prod_{i=1}^{n}(1 - q_i) = 1 - (1 - q)^n \tag{17}$$

where Z is the number of times the invasive species invades the ecosystem. The probability increases with the number of visiting boaters, n, and as n approaches infinity, invasion is virtually certain.

Bossenbroek *et al.* [4] describes boater movement throughout the country and gives the number of boats traveling to or within the Columbia River Basin in relation to other regions in the U.S. Updating the 2006 work to account for post-2007 invasion in other regions of the Western U.S., Bossenbroek (unpublished data) find the current probability of a successful invasion $\gamma(n)$ into the Columbia River Basin to be as high as 75 percent over the next twenty years.[10] The predicted relative number of boats n is 2,138. This corresponds to a per boat probability of invasion of 0.065 percent.

Large industrial sectors of the Columbia River Basin will be affected by a dreissenid invasion, particularly industries such as power and agriculture that depend on the services of large federal dams. Production in our CGE model occurs in a bi-level nest. The first nest combines capital and labor in a CES function to form a composite primary factor of production. The second nest combines this primary factor with intermediate inputs in

[10] The first of an increasing number of dreissenid mussel populations was discovered in the western United States in 2007, at least 1,600 kilometers west of previously known established populations. Initial invasions into the West were most likely a result of boater movements across the continent [3], but new beachheads of invasion exist in Colorado, specifically Pueblo Reservoir and Lake Granby, and the Colorado River watershed. Established populations in Lakes Mead and Powell have already led to downstream spread to the California Aqueduct and multiple reservoirs in California.

a Leontief production function, retaining the constant returns to scale assumption in the analytical model. For computational purposes, we model the dual problem for the firm, representing each sector with a cost-minimizing firm. Our nine production sectors are state and municipal power generation, federal power generation, independent power production, municipal water, irrigated agriculture, non-irrigated agriculture, fish hatcheries, recreational fishing, and a catchall miscellaneous sector. Of these, we expect significant efficiency losses in production for all power generation, municipal water, and irrigated agriculture.

Costs to firms are composed of primary costs (payments to labor and capital), costs of purchasing intermediate inputs, and indirect business taxes. The influence on industry costs by zebra mussel invasion is introduced to the model by factor productivity shocks. Following a zebra mussel invasion, affected industries respond by installing mitigation equipment and hiring people to monitor and control the effects, leading to efficiency losses. The dual equivalent of these factor productivity shocks are reflected in the primary factor cost (PVC_k [11]) functions' efficiency parameters

$$(\phi_k)^{-1} = \Delta^k(\phi_k^N)^{-1} \tag{18}$$

where Δ^k is the percentage change in industry k costs induced by the dreissenid invasion and ϕ_k^N is the sector's efficiency parameter in the absence of any cost impacts.

Primary costs are a function of regional output (DY_i), regional rental rate of capital (R), and the regional wage rate (W). They also depend on value added distribution parameters (δ_i), industry specific partial elasticities of substitution in value added (σ_i), and industry

[11] k = {state and municipal power generation facilities, federal power generation facilities, independent power producers, municipal and industrial water users, fish hatcheries, irrigated agriculture}

specific value added efficiency parameters (ϕ_i).

$$PVC_i = (\phi_i)^{-1} DY_i[\delta_i^{\sigma_i} W^{1-\sigma_i} + (1-\delta_i)^{\sigma_i} R^{1-\sigma_i}]^{1/(1-\sigma_i)} \tag{19}$$

Under threat of invasion, expected primary costs become

$$\begin{aligned} E[PVC_i] = {} & \gamma\Delta^k(\phi_i^N)^{-1} DY_i[\delta_i^{\sigma_i} W^{1-\sigma_i} + (1-\delta_i)^{\sigma_i} R^{1-\sigma_i}]^{1/(1-\sigma_i)} \\ & +(1-\gamma)(\phi_i^N)^{-1} DY_i[\delta_i^{\sigma_i} W^{1-\sigma_i} + (1-\delta_i)^{\sigma_i} R^{1-\sigma_i}]^{1/(1-\sigma_i)} \end{aligned} \tag{20}$$

or

$$E[PVC_i] = \Phi PVC_i^N \tag{21}$$

where $\Phi = [1-(1-q)^n]\Delta^k + (1-q)^n$. The firms' factor demands under uncertainty are

$$K_i = (\frac{DY_i}{AX_i})^{1-\sigma_i}[E[PVC_i](\frac{1-a_i}{R})]^{\sigma_i} = \Phi^{\sigma_i} K_i^N \tag{22}$$

$$L_i = (\frac{DY_i}{AX_i})^{1-\sigma_i}[E[PVC_i](\frac{a_i}{W})]^{\sigma_i} = \Phi^{\sigma_i} L_i^N \tag{23}$$

K_i^N and L_i^N are the factor demands without the threat of an invasion. To produce the same output as in the absence of an invasion, firms increase their factor demands, increasing costs of production and the price of the domestic good. Faced with higher prices, quantity demanded falls. The welfare effect of a dreissenid invasion depends on the relative size of the increases in domestic prices and payments to factors, which the households own.

Welfare changes are measured by the sum across households of equivalent variations following the tax policy. Each household has a nested utility function where the upper level represents the household's choice between total consumption (X) and leisure (l). This specification mirrors the optimization problem in the analytical model, where X now represents a composite of consumption goods. Each household maximizes

$$H = [(1-\beta)^{1/\sigma_L} X^{(\sigma_L - 1)/\sigma_L} + \beta^{1/\sigma_L} l^{(\sigma_L - 1)/\sigma_L}]^{\sigma_L/(\sigma L - 1)} \tag{24}$$

subject to

$$I = PX + W(1-\tau_L)l \tag{25}$$

where β is the percentage of total labor endowment devoted to leisure in the benchmark data, I is after-savings income, and σ_L is the elasticity of substitution between consumption and leisure. The price for the sub-utility from consumption, represented by X, is given by the price index

$$P_h = (\sum_i \alpha_{i,h} PQ_i^{1-\sigma_h})^{1/(1-\sigma_h)} \tag{26}$$

where PQ_i is the price consumers face for good i, $\alpha_{i,h}$ is the share of expenditures household h spends on good i, and σ_h is the elasticity of substitution for goods for household h.

The first order condition for each household's upper nest is

$$\frac{l}{X} = \frac{\beta}{(1-\beta)} \frac{P^{\sigma_L}}{[w(1-\tau_L)]^{\sigma_L}} \tag{27}$$

with the h subscript suppressed for each household. (27) is equivalent to (7) for the functional forms employed. We rearrange and use the household time constraint to get labor supplied by each household

$$L^s = T - \frac{\beta}{(1-\beta)} \frac{P^{\sigma_L}}{[w(1-\tau_L)]^{\sigma_L}} X \tag{28}$$

We use Ballard et al. [2] measurements for elasticity of substitution between leisure and consumption and percentage of labor endowment initially devoted towards leisure.[12]

[12] Their model has values for twelve household groups whereas our model has nine households; we, there-

All nonresidents are required to have a fishing license to fish in the Columbia River Basin. Our analysis considers an additional tax on out-of-state licenses that reduces the number of trips by nonresident boaters into the region and reduces the probability of invasion and the associated externality. We assume regulators cannot distinguish between anglers from zebra mussel regions and other out-of-state anglers, so all nonresident licenses are taxed. A direct correlation between boaters and anglers is also assumed. A license fee acts as a gatekeeper to other regional economic activity. If the angler does not show up, expenditures on hotels, gas, etc., will fall accordingly. The number of visiting anglers decreases with the price of a license. The demand curve for nonresident licenses is given by

$$license = license_0(1 + \tau_{NR})^{-\eta} \tag{29}$$

where η is the elasticity of demand for nonresident licenses, *license* is the number of nonresident licenses bought, $license_0$ is the number of nonresident licenses bought in our benchmark year, and τ_{NR} is the tax on nonresident licenses. Constant ratios of nonresident licenses to out-of-state boaters and total expenditures are maintained in the model such that $X_{NR} = PVE \times license$ and $n = BPL \times license$ where PVE is per visitor expenditure and BPL is number of nonresident boats per nonresident license in the benchmark data.

Demand equations are parameterized using data on nonresident fishing licenses from the U.S. Fish and Wildlife Services (USFWS) National Fishing License Report (grant program 9500). According to the USFWS, 758,207 nonresident licenses were sold by states in the Columbia River Basin in 2002.[13] These angler figures were converted into their economic

fore, match the two sets using the Bureau of Labor Statistics consumer price index inflation calculator between data years (http://www.bls.gov/bls/inflation.htm). If one of our income ranges includes more than one of Ballard *et al.*'s income classes, we take the average of the parameters in those classes.

[13] For demand and tax revenue, we use number of anglers given by USFWS. For probability of invasion we use number of boaters given by Bossenbroek. We assume the elasticity of boaters and anglers is the same, though since boaters likely spend more per trip than non-boaters, their elasticity is likely to be lower.

activity equivalent, matching them to the recreational fishing sector, to merge them into the CGE model.

We assume state agencies issue fishing licenses and collect the tax to reduce state labor taxes. Thus, we add the following constraint to the state government's decision problem

$$G = \tau_L wL + \tau_{NR} P_{NR} license \tag{30}$$

where the left side represents government revenues initially composed of only the labor tax and the right side represents revenues under the new tax policy. P_{NR} is the price for a nonresident license in the Columbia River Basin evaluated at the average during our data years.

4.1 Results

The key result is that corrective environmental taxes do not always lead to welfare improvements. Net changes in welfare to residents depend on the elasticity of demand for nonresident angling and the relative magnitudes of the revenue recycling effect, the positive externality in the primary welfare effect, and the negative externality in the primary welfare effect. We use our CGE model to measure the relative sizes of each of the effects for the Columbia River Basin.

Without a tax on fishing, threat of a zebra mussel invasion causes a \$4.16 million welfare loss across all households. This serves as our base for policy comparisons. Figure 1 shows the change in welfare to resident households following a tax on nonresident licenses for a range of semi-log coefficients on price near the values estimated by preliminary work[14], 0.005, 0.01, and 0.02. Total welfare change is shown in Panel A; the revenue recycling, positive externality in the primary welfare effect, and negative externality in the primary

[14] see supplemental material

welfare effects are shown in Panels B-D.

As the tax rate on nonresident fishing increases, the number of out-of-region boaters decreases, decreasing the probability of invasion. Tax revenues from license sales are used to reduce household labor taxes, providing the primary means of compensating resident households. For high elasticities ($\eta = 0.02$), taxing nonresident fishermen causes a net decline in welfare among Columbia River Basin households. For low elasticities ($\eta = 0.005$), a tax of 400 percent on nonresident fishermen maximizes welfare of regional households. For $\eta = 0.01$, which based on our analysis and comparison with other studies closely matches the true value for nonresident anglers in the Columbia River Basin, welfare is maximized at a tax rate of 175 percent, or \$22.58 added to the average price of a nonresident license. A 175 percent tax will increase total welfare by \$3.9 million over the no-tax scenario. We decompose these effects into the three parts.

4.2 Revenue recycling - Labor taxes are reduced causing household income to go up, increasing overall welfare.

To measure the size of the welfare effect from tax redistribution for the Columbia River Basin we first assume taxes from nonresident anglers are not used to adjust the labor tax or given back to the households in any way. The difference between welfare changes under this scenario and one in which revenues are used to lower labor taxes gives us the welfare gains to households of our compensation scheme and is shown in Panel B. This welfare change is comparable to the first two terms of equation (13) and measures the welfare gains from reducing the distortion in the labor market. With lower labor taxes, the real wage rises, households supply more labor, and household incomes rise.

4.3 Positive externality in primary welfare effect - Taxing nonresident consumption causes demand for locally owned factors to fall, reducing overall welfare.

Nonresident demand brings money into the Columbia River Basin. These additional revenues are a positive externality from nonresident demand, and taxing nonresidents will decrease the benefits to Columbia River Basin households. These changes are the positive externality in the primary welfare effect. We measure the size of this effect by setting the probability of a dreissenid invasion to zero but still levying a tax on nonresident consumption. The tax revenues are not given back to the household or used to adjust government expenditures in any way. Without an impact from the lost productivity of an invasion, this measure gives the welfare effect of imposing the tax, shown in Panel C. For highly elastic demand, welfare losses are significant. Visitors respond to the tax by reducing consumption, causing labor demanded and income to households to fall.

4.4 Negative externality in the primary welfare effect - Taxing nonresident consumption decreases the probability of invasion, causing overall welfare to rise.

The final component of welfare change is the benefits to households from correcting the externality and is the part of the primary welfare effect from the negative externality. To measure this effect, we take the difference of an impact with a probability of invasion and a tax policy and an impact with just the tax policy and no probability of invasion, both without redistribution of tax revenues. This gives a measure of the externality with a tax policy. Subtracting this number from the impact without any policy ($4.16 million) gives the reduction in the externality from the tax, shown in Panel D. Higher elasticities lead to larger reductions in nonresident visitors and larger benefits from correcting the negative externality.

In summary, examining Figure 1, taxing nonresident consumption does not ensure welfare gains for Columbia River Basin households. For very low elasticities, welfare changes are positive due to the ability to raise tax revenues and correct the preexisting distortion in the labor market. As the elasticity increases the ability to correct the externality is important to achieving welfare gains - up to a point. If demand is highly elastic, the number of visitors falls enough to cause large drops in regional production and net welfare losses.

An extreme policy alternative to taxation is completely shutting down the fishery to outside anglers. This will drive the probability of invasion to zero (or near zero) but all tourist revenues associated with recreational fishing will be lost. Our model predicts that such a measure would lead to \$15.7 million in welfare losses. Comparing this to the \$4.16 million in lost welfare that results from the threat of invasion, the non-market value of preventing a dreissenid invasion into the Columbia River Basin would have to be about 2.7 times the market impact to justify shutting down the fishery. For perspective, our model estimates that costs associated with the most recent Biological Opinion [27] aimed at salmon recovery in the Columbia River Basin will lead to market-based welfare losses of \$18.5 million.[15] More moderate policy options include the installation of monitor stations and cleaning facilities at boat launch sites. This would have the effect of imposing additional costs on all anglers, reducing their numbers, in exchange for a reduced probability of introduction per boat. Lower probability of invasion would reduce the wage distortion resulting from the firms' uncertainty, leading to large-scale benefits. Because the policy is not revenue generating, however, it cannot offset preexisting distortions in the labor market. Policy makers would have to consider sensitivity of welfare changes between the

[15] Estimates on the non-market to market costs of climate change, for example, give ratios between 1-1.5 and 4-1 [30], and nonmarket value of in-stream uses of water are reported to be 1.5 times the market value [20].

two methods of reducing the probability of invasion, reducing the per boat probability versus reducing the number of boats entering the basin. We do not have data on boater reactions to cleaning stations, though this is a worthwhile extension for policy comparisons and comprehensive cost-benefit analysis.

Two caveats are worth noting. First, we do not address the welfare of nonresidents of the Columbia River Basin. Taxing nonresidents is likely to cause welfare losses to frequent visitors. Second, levying a tax on licenses sold by states in the Columbia River Basin will decrease visitors trips into the basin, but we cannot be sure they will stay home. The problem may shift elsewhere, raising the threat of invasion into other pristine bodies of water.

5 Conclusion

Invasive species can be introduced to ecosystems through indirect relations to trade. For aquatic mussels, recreational boating and fishing by tourists is the main threat. To the degree that economists connect these invasions to imports in modeling and policy responses, resulting policies may miss the mark and cause even greater economic harm. The trade literature makes a strong case for modeling local services provided to visitors as regional exports, for all of the same reasons recreational fishing and boating by out-of-state residents should also be modeled as exports. Levying taxes on these activities may reduce the risk of invasion, but it can also cause large drops in regional income.

Our example of the Columbia River Basin highlights the danger in uniformly prescribing a corrective tax to the problem of invasive species. For highly inelastic demand, introducing a tax on non-resident fishing licenses may help alleviate the damages from dreissenids. The tax can reduce the probability of invasion and the negative externality non-resident anglers bring to the economy, but if non-resident anglers are sensitive to taxes levied on the license price, the area will see large reductions in visits from outside anglers and drops in household income. Furthermore, reduced visitor numbers in the Columbia River Basin are likely to lead to increased numbers of visitors in other Western waters. Ultimately, policies limited to the Columbia River Basin will be self-defeating. As anglers substitute other fishing holes for those of the Columbia River Basin they increase the probability of an invasion into those areas, and policy makers in the Columbia River Basin will have to monitor movements from these new dreissenid sources.

A Appendix derivation of welfare effects

To examine the welfare effects, the resident's utility function is totally differentiated and divided by λ. As λ is the marginal utility of wealth, $\frac{dU}{\lambda}$ is the marginal change in resident welfare expressed in monetary units.

$$\frac{dU}{\lambda} = \frac{U_X dX_R}{\lambda} + \frac{U_l dl}{\lambda} + \frac{U_Q dQ}{\lambda} \tag{A.1}$$

Substituting in the resident first order conditions, recalling $dQ = 0$ in equilibrium, and setting the price of the good as the numeraire, gives

$$\frac{dU}{\lambda} = dX_R + w(1 - \tau_L)dl \tag{A.2}$$

Totally differentiating the resident's time constraint and substituting for dl in the welfare equation,

$$dT = dl + dL = 0 \tag{A.3}$$

$$\frac{dU}{\lambda} = dX_R - w(1 - \tau_L)dL \tag{A.4}$$

Incorporating the first order conditions of the firm

$$\frac{dU}{\lambda} = dX_R - [\phi\gamma + (1-\gamma)](1-\tau_L)dL \tag{A.5}$$

γ is the equilibrium probability of invasion from the firm's first order conditions and is associated with the profit maximizing level of output.

It is useful to express welfare with as few variables as possible, and preferably in variables exogenous to the resident household. This requires several steps. First, the resource constraint is totally differentiated and used to substitute for dX_R.

$$dL = dX_R + dX_{NR} \tag{A.6}$$

Second, the government budget constraint is totally differentiated. Since revenues from the environmental tax are used to lower the labor tax, total government revenues remain unchanged.

$$dG = \tau_{NR}dX_{NR} + d\tau_{NR}X_{NR} + \tau_L d(wL) + wLd\tau_L = 0 \tag{A.7}$$

Subtracting dG from the welfare function leaves it unchanged. Solving for the welfare change with tax effects,

$$\frac{dU}{\lambda} = -dX_{NR}(1+\tau_{NR}) - d\tau_{NR}X_{NR} - wLd\tau_L - \tau_L L dw + \gamma(1-\phi)dL \tag{A.8}$$

Dividing both sides by $d\tau_{NR}$

$$\frac{dU}{\lambda d\tau_{NR}} = -\frac{dX_{NR}(1+\tau_{NR})}{d\tau_{NR}} - X_{NR} - wL\frac{d\tau_L}{d\tau_{NR}} - \tau_L L\frac{dw}{d\tau_{NR}} + \gamma(1-\phi)\frac{dL}{d\tau_{NR}} \tag{A.9}$$

Defining the price elasticity for visitor demand as $\eta = \frac{dX_{NR}}{d(1+\tau_{NR})}\frac{1+\tau_{NR}}{X_{NR}}$ allows (A.9) to be rewritten as (13).

B Figures

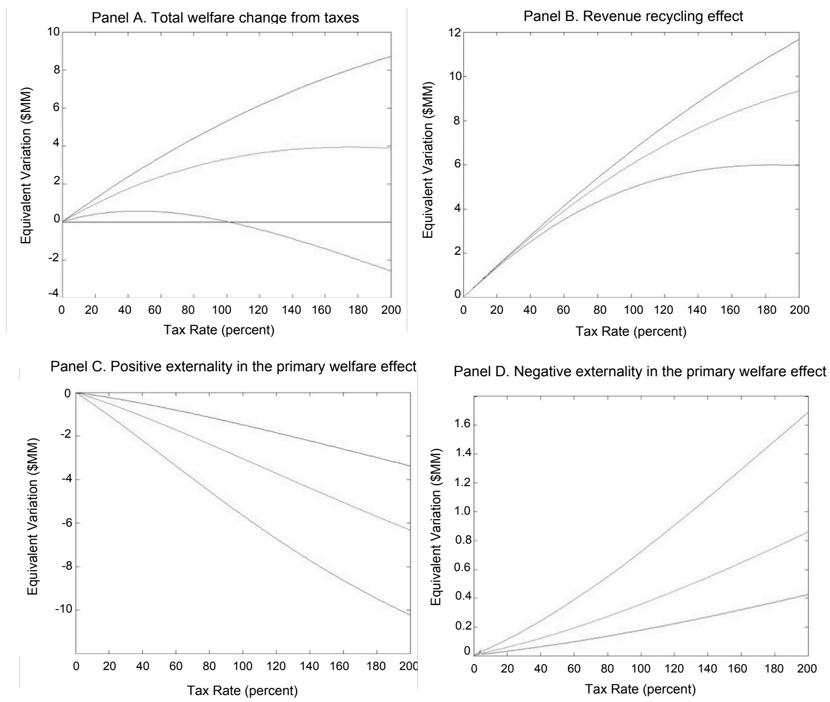

Figure 1: Welfare effects of environmental tax

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