Title: Stepping stones for biological invasion: A bioeconomic model of transferable risk

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Stepping stones for biological invasion: A bioeconomic model of transferable risk

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Abstract:

Herein we model the widespread dispersal and management of an invasive species as a weak-link public good. The risk of introduction is driven in part by economic activity, is influenced by policies directed at the risk, and economic activity responds/adapts to the risk. Framed around recent introductions and rapid spread of dreissenid mussels in the Western United States, we find three key results. First, partial equilibrium estimates of welfare loss are significantly overestimated relative to general equilibrium estimates. If ecosystem services and market goods are substitutes the partial equilibrium bias is greater than if they are compliments. Second, well-intended policies do not necessarily reduce overall risk; risk reduction actions can transfer risk to another time or location, or both, which may increase total risk. Third, policies of quotas and inspections have to be extreme to improve welfare, with inspections having advantages over quotas.

Keywords: bioeconomic, invasive species, risk, weak-link, welfare

1. Introduction

We investigate three sources of bias in valuation methods for invasive species risk: failure to consider substitution possibilities between goods (partial equilibrium analysis), failure to consider nonseparability of ecosystem services with market goods (general equilibrium externalities), and failure to consider substitution possibilities between ecosystems (spatially transferable risk). The first two biases are known in the literature, and we offer insight on the size of the bias for a specific example. Our work on spatially transferable risk is novel. We develop the concept in detail and show how it may undermine typical invasion prevention strategies.

These biases result from failure to integrate feedbacks between the economic and ecological systems (e.g., O'Neill 1997, Pimentel et al. 2000, Pimentel et al. 2005). Such "partial equilibrium" approaches provide estimates that do not address key interactions within the economic system and between human and ecological systems. When these interactions are important, general equilibrium methods are more appropriate (Kokoski and Smith 1987, Crocker and Tschirhart 1992, Finnoff and Tschirhart 2007, Bossenbroek et al. 2009). We show when humans adapt to risk and changes in the ecological system, well-intended policies may not reduce overall risk. Risk reduction actions can *transfer* the risk to another time or location, or both, which may not reduce total risk (e.g., Bird 1987, Shogren and Crocker 1991). The general equilibrium approach presented here reveals that policies that reduce nonresident boaters by as much as 95% are sometimes required for an overall welfare improvement. Policies that reduce the number of nonresident boaters by less than 95 percent can lead to welfare degradations exceeding those of doing nothing.

We develop the model within a discussion of recent introductions and rapid spread of zebra and quagga mussels (*Dreissena polymorpha* and *D. bugensis*, collectively referred to here as dreissenids) in the western United States, and the threat of introduction into the Columbia River Basin. The Columbia River Basin is well suited to tell such a story; we present the model within this context to provide clarity. Our numerical results are intended to comment on various modeling approaches, not to serve as impact measures of specific policies. We acknowledge the impact measurements are sensitive to choices of parameter values and assumptions, and should be treated accordingly (Shoven and Whalley, 1984).

Dreissenids are small freshwater mollusks that arrived in the U.S. through shipping channels connecting the East Coast and Europe. Following establishment, 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 (O'Neill 1997, Connelly et al. 2007). They are also prolific filter feeders, causing ecosystem-wide damages in the bodies of water they invade (Marsden and Chotokowski 1998; Nalepa 1998; Ricciardi, Neves, Rasmussen 1998; Strayer et al. 2004). Introduction in the Great Lakes led to rapid spread throughout the Eastern United States, but further spread west was slowed by regional policies and geographic isolation (Horvath et al. 1996; Johnson, Bossenbroek, Kraft 2006). The Rocky Mountains and the Continental Divide separate infested waters in the East from those in the West and have provided barriers to natural introduction to the West.

These natural barriers make the Columbia River Basin an ideal case study for our purposes. The Basin is ecologically isolated from, but economically integrated with, other regions throughout the U.S. The Columbia River Basin is a 675,000 square kilometers drainage area in the U.S. Pacific Northwest. It was upgraded to one of six of the Nation's Great Water Bodies in the EPA's 2006-2011 Strategic Plan, joining the likes of the Great Lakes and the Gulf of Mexico (USEPA 2006). Nonresident anglers and boaters spend about $1 billion in the local economy each year. (American Sportfishing Association, 2008). No water bodies in the Columbia are connected with currently invaded bodies of water, making human transport the only possible vector of dreissenid introduction.

The first discovery of expanding dreissenid mussel populations west of the Rockies was in 2007, at least 1,600 kilometers west of previously known established populations (100th Meridian Initiative 2007). These new invasions were most likely a result of boater movements across the continent (Bossenbroek et al. 2007). New beachheads in the Colorado River watershed, however, now threaten the Columbia River Basin. We call these new sources of risk as 'stepping stones' for invasion. Stepping stones are ecosystems that currently pose no direct risk of introduction, but because of their ties with invaded ecosystems, may become invaded themselves, and pose an indirect risk of introduction. Stepping stones are the greatest source of risk to the Columbia River Basin.

We begin by describing key parts of the bioeconomic model. We then present impacts for a dreissenid invasion into the Columbia River Basin. In section 3 we investigate the effects of our three biases and show how stepping stones affect the use of quotas and inspections to prevent invasion. The final section concludes with research and policy recommendations.

2. Methods

We use a bioeconomic computable general equilibrium (CGE) model to measure welfare changes from a dreissenid invasion into the Columbia River Basin and from policy measures designed to reduce the risk of invasion into the basin. Threat of invasion is modeled using a production constrained gravity model of boater movement and a probability function dependent on boater arrivals. Risk of invasion changes the expected state of the ecosystem, which affects expected costs to firms and household utility. Firm and household reactions are modeled in general equilibrium. These reactions in turn affect variables in the gravity model and the probability of invasion, completing an adaptive loop between the ecological and economic systems. For brevity we include in the text only the features of the model that deviate significantly from standard CGE models (e.g., DeMelo and Tarr 1992, Shoven and Whalley 1992). Appendix A provides the full mathematical description. Computer code and benchmark data are posted on the corresponding author's website.

2.1. Threat of invasion

Figure 1 illustrates the threats to the Columbia River Basin (*C*). Risk of invasion comes from two regions, U.S. sources east of the Continental Divide (*E*) and other western basins. The other western basins are the Pacific Northwest excluding the Columbia (Pa), California River Basin (Ca), Great Basin (G), Upper Colorado River Basin (U), Lower Colorado River Basin (L), and Rio Grande River Basin (R). Let the set of all possible basin dreissenid sources be $b \in B = \{E, Pa, Ca, G, U, L, R\}$ and the set of all western basins be $w \in W = \{Pa, Ca, G, U, L, R\}$.

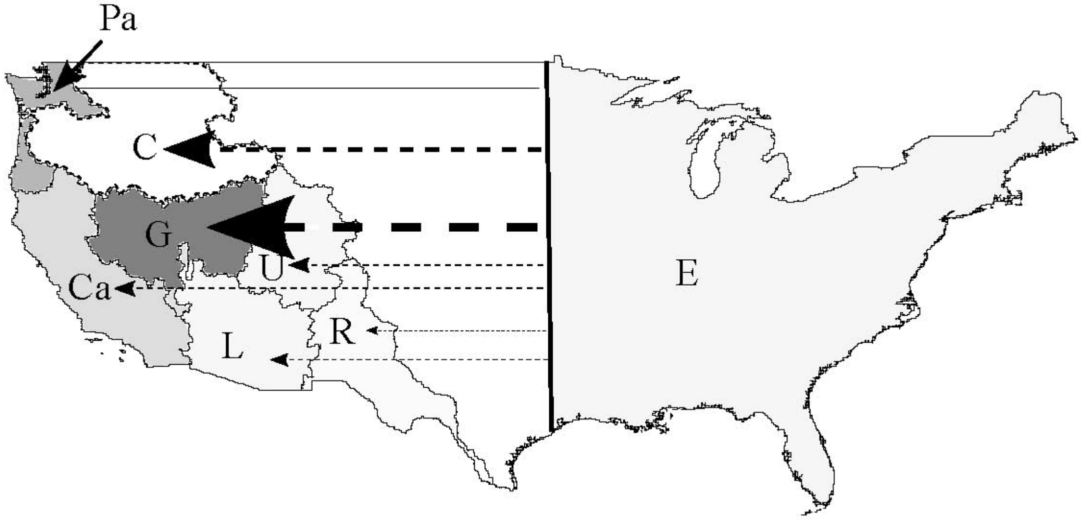

Figure 1. Sources of risk for invasion into the Columbia River Basin
Until recently, the greatest risk of dreissenid introduction into the Columbia River Basin (C) was east of the 100th Meridian and Continental Divide (E). Additional threats now come from the Pacific Northwest excluding the Columbia (Pa), California River Basin (Ca) Great Basin (G), Upper (U) and Lower (L) Colorado River Basins, and the Rio Grande River Basin (R). Solid lines indicate primary threats of invasion from links with the East. Dashed lines indicate secondary threats from links between the Columbia River Basin and other western basins.

The unique features of the Columbia and other basins in the west attract thousands of visitors each year. We relax the usual small country assumption for recreational export demand and model demand combining a constant elasticity of demand curve (Dervis et al. 1982) with a production constrained gravity model (Bossenbroek et al. 2007).[*] Without dreissenids and under benchmark economic conditions, n_{ij} visits by boaters from basin *i* to *j* are endogenously determined according to forces of attraction in

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[*] Sales of services, such as recreational fishing, to nonresidents are modeled as exports following trade literature on consumer services (see for example Deardorff 2005) despite consumption occurring within the Columbia River Basin.

the gravity model - surface area of water, the number of boats housed at the source basin, the distance between basins, and the total number of basins *N*. Boaters react to changes in the cost of boating based on elasticities of demand. Changes in cost arise due to government pricing policies or due to ecosystem changes that make obtaining a given level of boating more expensive (discussed below). Forces of attraction in the gravity model shift the demand curve, and price changes cause movements along the demand curve.

The probability of invasion into basin j caused by a boater from basin i is given by a binomial distribution

$$\varphi_{ji}(n_{ij} | Z_j) = \Pr(D_{ij} \geq 1) = 1 - \Pr(D_{ij} = 0) = 1 - (1 - q_{ij})^{n_{ij}} \tag{1}$$

where Z_j is a vector of ecological attributes for basin j that determine its susceptibility to invasion, D_{ij} is the number of successful dreissenid invasions from i into j, and q_{ij} is the per boat probability of invasion. Aggregate probabilities of invasion into a given basin are denoted by dropping the source subscript; for example, φ_C is the aggregate probability the Columbia Basin becomes invaded from any source.

If the threat of invasion was only from the East, $\varphi_C(n_{EC} | Z_C) = 1 - (1 - q_{EC})^{n_{EC}}$. The actual probability of invasion into the Columbia, however, depends on the probability of invasion into other western basins and the likelihood that these regions serve as stepping stones for invasion into the Columbia. Accounting for potential invasion in other basins in the West, realized per boat probability of introduction from basin w into the Columbia is $q_{wC}\varphi_w$, and the realized probability of the Columbia becoming invaded depends on total boats n entering the Columbia,[†]

$$\varphi_C(n|Z_C) = 1 - (1 - q_{EC})^{n_{EC}} \prod_w (1 - q_{wC}\varphi_{Ew})^{n_{wC}} \tag{2}$$

Equation (2) captures the idea behind multiple environmental niche models, which suggest Western waters are conducive to the establishment of dreissenids, and major waterways would likely be colonized within a few years (Strayer 1991, Drake and Bossenbroek 2004, Bossenbroek et al. 2007, Whittier et al. 2008).[‡] Rapid spread and lag time between introduction of dreissenids and their discovery imply threats from basins even with no current discovery (Costello et al. 2007). Threats in our model are understood to be current.

2.2. The CGE Model

There are nine producing sectors indexed by $s \in S$ = {state and municipal power generation facilities, federal power generation facilities, independent power producers, municipal and industrial water users, commercial fishers and hatcheries, irrigated agriculture, (non-irrigated) agriculture, recreational angling services, and a catchall miscellaneous sector}. Our treatment of household behavior follows Carbone and Smith (2008). Nine representative households distinguished by income maximize utility, taking the state of the ecosystem as given, subject to budget constraints. Assume the state of the ecosystem is nonseparable with market angling services, which together produce

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[†] Our probability calculations are conservative in that the probabilities of invasion between other western basins are independent. We do not include the probability of introduction from western basins into other western basins.

[‡] Less than a decade after their discovery in North America (in Lake St. Clair), zebra mussels had spread throughout the Great Lakes and down the Mississippi River from Minnesota to New Orleans (USGS 2008).

recreational boating. Ecosystem services provide rents to households and are treated similar to rents in Hertel and Tsigas (1997) and Jensen and Rasmussen (2000). Households purchase environmental quality at a positive price; the value is then transferred back to the households lump sum as income.

The link between the threat of invasion and the regional economy is through visitor export demand (number of boaters). The external effects of this economic activity and its remediation lie at the center of the following analysis. We investigate general equilibrium externalities and experiment with various degrees of substitutability between the state of the ecosystem and market goods.

2.3 Policy Scenarios

Because no current technology exists to reduce the aggregate abundance of dreissenid mussels in natural waterways, eradication policies are likely to be ineffective. Policies are only expected to affect the probability of invasion, not the severity. We consider quotas and inspection policies aimed at reducing risk of invasion (Shogren 2000).

2.3.1. Quotas

Establishing a quota on the number of nonresident boaters is a simple and low-cost method of reducing the number of potentially infected boats. Many states limit the number of licenses sold to out-of-state residents for recreational activities such as hunting, and limits could be imposed for boating. If a cap of $\overline{n}$ boaters is imposed, and nonresident boaters arrive in proportions equal to those prior to the policy,

$$n_{bC} = \bar{n}\frac{n_{bC,0}}{\sum_{b} n_{bC,0}} \tag{3}$$

Naught (0) subscripts indicate benchmark values. Boaters denied entry into the Columbia River Basin can launch in other Western waters, increasing the probability these basins become invaded and creating sources of risk much closer to home. Boaters who choose to launch elsewhere do so based on the parameters of the gravity model (i.e., attractiveness and distance) that do not change due to policies in the Columbia River Basin. These boaters increase their boating at these locations in equal proportion to their boating prior to the Columbia policy,

$$n_{Ew} = n_{Ew,0} + (\sum_{b} n_{bC,0} - \bar{n}) \times \frac{n_{EC,0}}{\sum_{b} n_{bC,0}} \times \Gamma \times \frac{n_{Ew,0}}{\sum_{w} n_{Ew,0}} \tag{4}$$

$(\sum_{b} n_{bC,0} - \bar{n})$ is the number of boaters turned away from the Columbia River Basin by the quota; $n_{EC,0} / \sum_{b} n_{bC,0}$ is the fraction of boaters traveling to the Columbia who are from the East; Γ is the percentage of turned away boats from the East that launch in other basins in the West; and $n_{Ew,0} / \sum_{w} n_{Ew,0}$ is the percentage of boats launching in all other western basins in the benchmark equilibrium from the East that enter basin *w*. Equation (4) contains only constant parameters and the policy variable for quotas; our treatment of entry decisions into other western basins does not include behavioral adjustments following a policy in the Columbia.

2.3.2. Inspection

Enforcement agencies can also undertake boat inspections to reduce the per boat probability of an invasion. An inspection policy is captured by the number of boats inspected from each region I_b. Inspections are costly relative to a quota system. These costs are financed with fines imposed on infested boats. If an inspection finds mussels, the boat is cleaned, fined *f*, and allowed to enter. Inspections reduce the per boat probability of invasion to

$$\varphi_C = 1 - (1 - q_{EC})^{n_{EC} - I_E} \prod_w (1 - q_{wC}\varphi_w)^{n_{wC} - I_w} . \tag{5}$$

Assume boaters from a given region are equally likely to be inspected and fined. Define P_I as the per inspection cost to the government. A balanced government budget implies

$$P_I \sum_b I_b = f\left(I_E q_{EC} + \sum_w I_w q_{wC} \varphi_w \right) \tag{6}$$

The left side of equation (6) is total cost of inspections. The right side of equation (6) is expected total revenues from inspections. $q_{wC}\varphi_w$ is the probability of a boat from basin *w* being infected; $f I_w q_{wC} \varphi_w$ is expected revenue from basin *w*. Based on their probability of inspection and likelihood of carrying dreissenids, boaters calculate their expected fine $E_b[f]$ and adjust their demand accordingly, $E_b[f] = f \times (I_b / n_{bC}) \times (q_{bC}\varphi_b)$ where I_b / n_{bC} is the probability of being expected.

2.4 Welfare Analysis

Vectors of prices in the benchmark scenario *b* and impact alternate *a* are given by $\overline{P}^b$ and $\overline{P}^a$. Our comparison of partial and general equilibrium scenarios are defined by the number of prices within $\overline{P}^a$ that adjust following an invasion (Kokoski and Smith 1987). In partial equilibrium, final demand is calculated holding prices in non-impacted sectors fixed at benchmark levels. For example, if $(P_1^b, P_2^b, P_3^b, .., P_9^b)$ is the vector of benchmark prices, $(P_1^a, P_2^a, P_3^a, .., P_9^a)$ is the vector of prices allowing full (general equilibrium) adjustment following an impact, and the first two sectors are directly affected by an invasion, then our partial equilibrium analysis allows the adjustment $(P_1^a, P_2^a, P_3^b, .., P_9^b)$. Prices in impacted sectors will be miss-specified relative to prices in non-impacted sectors.

Welfare effects of the impacts of a dreissenid invasion are evaluated in terms of compensating variation measures. Define *E(P,U)* as the unit expenditure function associated with achieving utility level *U* with prices *P*. Benchmark calibration is done so $E(\overline{P}^b, U^b)$ equals unity. Percentage changes in welfare are $CV = 1 - E(\overline{P}^a, U^b)$, to which we multiply benchmark disposable income for a measure of welfare change in dollars (Rutherford 2009).

2.5 Data and Parameterization

Calibration of the gravity model uses national boater movement data and is described in Bossenbroek et al. (2007). Probabilities are calculated treating the entire invasion history (1988-2007) in the East as one event. We then calculate the probability a given basin will become invaded over a similar time horizon. All probabilities are for an invasion in twenty years. Figures for boater movement are annual and are relative based on total U.S. boater movement in the 2004 data year. Cost impacts are annual based on risk over the twenty years. The CGE is based on a benchmark dataset from an IMPLAN (MIG, 2004 data year 2001) derived social accounting matrix for counties in the Columbia River Basin. The recreational fishing sector was created out of the miscellaneous sector using data from the American Sportfishing Association (2008). They report $1.9 billion in total retail sales from anglers in the Columbia River Basin, representing 1.5% of the miscellaneous sector. The same study also reports over 23 million angler days in the Columbia in 2006. Kaval and Loomis (2003) report $39.70 per person per day use values for outdoor recreation. This gives total rents for environmental quality of $930 million, or an implied share of environmental quality in recreational fishing of one third.

Power sectors, commercial and recreational fishers, and the region's irrigated agriculture producers will face direct costs to control the mussels, leading to reduced capacity and efficiency losses (Armour et al. 1993, Leung et al. 2002, WSTB 2004, USEPA 2006). Expected industry-specific increases in unit costs used for this study are: federal power (0.30%), state and local power (0.22%), independent power (0.10%), irrigated agriculture (0.20%), municipal water (0.12%). Direct costs to hydroelectric power plants are based on Pacific States Marine Fisheries Commission (PSMFC) (Phillips 2005), produced for this project. **I**mpacts to nonfederal hydroelectric facilities use the PSMFC report as a baseline and scale impacts according to Northwest Power and Conservation Council data on power facilities (July 2005). Impacts to fossil fuel and nuclear power generation facilities are based on O'Neill (1997). Impacts to water treatment plants are based on Deng (1996). Using data from the USDA Census of Agriculture (2002) we allocated farming costs between irrigated and non-irrigated agriculture and limited direct impacts to pumping mechanisms and control costs at water distribution facilities (e.g., those operated by the Bureau of Reclamation) that are likely to be passed on to water users. Impacts in commercial fishing follow Rothlisberger, et al. (2009). See Warziniack (2008) for detailed calculations of these direct impacts industry.

Impacts to environmental quality are described by implied prices to obtain a given level of environmental quality as it relates to observed changes in demand for recreational fishing. Recreational fishing days have declined by about fifteen percent due to social changes and ship-borne invasive species in the Great Lakes (Rothlisberger et al. (2009). Bennear, Stavins, and Wagner (2005) report an own price elasticity for recreational fishing of about -0.25. We assume one fourth of the change reported in Rothlisberger et al. is attributed to ecosystem change, implying a 15 percent increase in cost of obtaining ecosystem services.[§]

3. Results

We first present results relating to the three biases: partial equilibrium analysis, separability assumptions, and transferable risk. We then detail how these biases affect prevention policies. Table 1 displays price and quantity changes for six model specifications. The first column summarizes general equilibrium impacts. The second and third columns illustrate the consequences of two partial equilibrium perspectives, the second when only prices in impacted sectors are allowed to adjust and the third when

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[§] The choice to attribute one fourth of the change in fishing to ecosystem services is admittably arbitrary. There is little work on how recreational fishing demand changes due to invasive species though much anecdotal evidence suggests it is an important driver. The most we can say is that it should be no more than fifteen percent.

only the price of capital and labor adjust. Columns four and five consider the consequences of alternative substitutability assumptions in the general equilibrium specification. The fourth column halves the elasticity of substitution between angling and ecosystem services, while the fifth doubles the elasticity. The sixth and final column presents results when stepping stones are not addressed.

The bottom row of Table 1 shows the size of each bias, measured as percent deviations from the CGE baseline. Although these results are merely intended as an illustration, in this example the partial equilibrium bias is larger than ignoring primary sources of risk shown in the no stepping stones scenario. In contrast, the bias relating to separability is relatively minor.

Result 1. Partial equilibrium estimates of impacts are biased upwards when ecosystem services and market goods are substitutes.

Support: The biases inherent in partial equilibrium analysis have been shown by Whalley (1975) and Kokoski and Smith (1987). Following direct impacts in a given sector, the price of the good rises and the relative price of other goods fall. Quantity demanded for each good changes, causing factors to be reallocated across sectors, influencing factor payments. Partial equilibrium assumptions that do not let the prices of other goods and/or the prices of factors adjust discourage substitution away from impacted sectors. Agents are exposed to more damages than they would otherwise be under general equilibrium assumptions, and welfare measures will be biased accordingly.

The first partial equilibrium scenario in column two of Table 1 (simple partial equilibrium, ‘SPE’) examines each market in isolation. Direct costs in impacted sectors are assumed to pass directly to households in the form of higher domestic prices in those sectors. Final consumption prices are calculated allowing mixing with imported goods following Armington assumptions. From these prices we calculate expenditure functions and associated welfare effects. Column three shows the extended partial equilibrium treatment (EPE) holding prices in non-impacted sectors fixed but allowing factor prices to adjust. This scenario accounts for reductions in factor demands that accompany reductions in demand for goods.

Indices for impacted industries $P_{impacted}$, non-impacted $P_{non\text{-}impacted}$, and all prices P_{all} are used to compare net effects to prices and quantities in impacted and non-impacted sectors. Impacted prices in SPE are similar to the GE scenario, but non-impacted prices are considerably higher. Fixing incomes keeps incomes higher in SPE than any other scenario, but it is insufficient to offset the price differential. Allowing factors to adjust in the EPE. keep prices lower than in SPE, but with reduced income, welfare losses are larger under EPE than under SPE.

Variable	GE	SPE	EPE	GEComp	GESub	GE w/o stepping
$P_{impacted}$	1.0150	1.0151	1.0145	1.0153	1.0144	1.0103
$P_{non\text{-}impacted}$	0.9997	1.0000	1.0000	0.9997	0.9997	0.9998
P_{all}	1.0001	1.0004	1.0004	1.0002	1.0001	1.0001
Inc. Index	0.9995	1.0000	0.9988	0.9995	0.9995	0.9997
Probability	1.0000	1.0000	1.0000	1.0000	1.0000	0.6800
Impact	-64.4634	-88.5470	-89.2493	-67.3046	-58.9312	-44.5054
Bias	-	0.3736	0.3845	0.0441	0.0858	0.3096

Table 1. Comparison of Impact Scenarios
Price indices are Laspeyres price indices, defined by $\sum_s P_s X_{s,0} / \sum_s P_{s,0} X_{s,o}$. The income index is the proportion of benchmark payments to factors. bias = (Scenario Impact - CGE impact) / (CGE Impact).

Result 2. Welfare changes are smaller when impacted nonmarket goods are substitutes for market goods; larger when nonmarket goods are complements to nonmarket goods.

Support: Carbone and Smith (2008) address the role of substitutability in what they call "general equilibrium externalities"; we show these impacts in the fourth and fifth columns in Table 1. Column four is a repeat of the GE scenario with the elasticity of substitution set to half the benchmark value (complements, GEComp) while column five has twice the elasticity of substitution (substitutes, GESub). The primary consequence follows from the price or recreation (not shown in the table but a component of $P_{impacted}$). With less substitutability (GEC), there is less variation in the ratio of demand for ecosystem services to angling services following an impact to ecosystem services. When the goods are substitutes relative prices send a signal to reallocate consumption to less affected sectors. These forces are nonexistence when the relationship is complementary.

In the absence of substitution, the price of recreation rises by more than if substitution were possible, and consumption of recreation declines further.

Result 3. Not addressing the invasive stepping stones biases impacts downward and may prevent effective use of quotas and inspections to control risk.

Support. The last column in Table 1 considers a scenario when sources of invasion in the West are not addressed. The result is straightforward - when probability of invasion is underestimated, expected impacts are underestimated. More importantly, in the presence of stepping stones, policies to control risk, even when all sources of risk are understood, may be ineffective. This result matters for the formulation and deployment of policies trying to reduce the risk of invasion and has not been addressed in the literature. Now we investigate its implications for the policy alternatives, quotas and inspections.

3.1 Policy implications of stepping stones

The policy implications depend on two key factors in the stepping stone idea: geographic isolation and economic isolation. Geographic isolation has been the primary force preventing a dreissenid invasion in the Columbia River Basin. As aquatic invaders, dreissenids eventually die when out of the water,[**] leading to a small per boat threat of invasion from the East.

All basins in the West experience some level of economic isolation. Transportation costs and amenity differences between basins prevent perfect substitution between western basins and with eastern locations. Regionally specific policies such as

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[**] The 100th Meridian Initiative recommends waiting at least 30 days after boating in dreissenid sources before launching in uninfested waterways. This safety window varies with weather conditions. In continuously freezing weather, three days is likely to be adequate, and in the dry Southwest, two weeks may be adequate. In cold, but not freezing, humid weather in the East, the recommended waiting time exceeds 100 days (100th Meridian Initiative). This window may allow invasion from the East if boats are removed from a source in the East and immediately taken to the Columbia River Basin.

quotas and inspections increase economic isolation for the region in question. Because the relative cost of angling in other western waters decreases following policies, their economic isolation can decrease. In the absence of any policies encouraging additional economic isolation, the gravity model estimates 2,005 boaters traveled from dreissenid-infested waters to the Columbia River Basin prior to the Western invasions in 2007. The probability of invasion in the Columbia River Basin was 68 percent, giving a per boat probability from the East into the Columbia of $q_{EC} = 1 - (1 - 0.68)^{1/2005} = 0.0568$ percent. The per boat probability is relatively small, but because of the binomial probability function the aggregate probability of invasion grows rapidly. For example, the probability of invasion reaches 50 percent with only 1,200 boats. Similar per boat probabilities of invasion from the East are calculated: see Table 2 for all western basins.

Western basin (w)	Boats traveling from East to basin ($n_{Ew,0}$)	Boats traveling from basin to Columbia ($n_{wc,0}$)	Per boat probabilities of invasion into basin (percent) (q_{Ew})
Pacific Northwest	170	19881	0.0555
California River	801	9788	0.0538
Great Basin	3424	33772	0.0554
Upper Colorado	851	2049	0.0543
Lower Colorado	653	1504	0.0546
Rio Grande	360	101	0.0551

Table 2. Boater movement and basin probabilities

Quotas: The probability of invasion can rise with stricter quotas (smaller $\bar{n}$) if the rate of change in probability of invasion from the West exceeds the rate of change in probability from the East. This condition is more likely to hold if 1) the number of boaters to the Columbia from the West is high relative to the number of boaters from the East, 2) biological conditions are suitable for an invasion into the West, so the per boat probability of invasion from the East to West q_{Ew} is high, 3) the per boat probability of invasion into the Columbia from western waters q_{wC} is high relative to that from the East q_{Ec}, and 4) the marginal change in boaters into the West is high. In the case of the Columbia, the first two criteria are satisfied. Boaters from the East represent only three percent of nonresident boaters in the Columbia, and biological niche models show most western waters to be suitable dreissenid habitat (Strayer 1991, Drake and Bossenbroek 2004, Bossenbroek et al. 2007, Whittier et al. 2008).

The third criteria is likely to hold due to shorter transport times and higher survival rates of hitchhiking dreissenids to closer western waters. Our gravity model, however, predicts lower per boat probabilities of invasion into western basins; western basins have relatively fewer distance-independent amenities (e.g., surface area of lakes) than the Columbia. The fourth criteria may hold for some but not all western basins. Boaters from the East frequent the Columbia in considerably higher numbers than for most other basins in the model. The Columbia's closest neighbors, the Pacific Northwest and California Basins, receive few boaters from dreissenid sources, but their proximity to the Columbia makes them viable substitutes for anglers faced with strict policies in the Columbia. Over 19,000 boaters from the Pacific Northwest and over 9,700 boaters from the California visit the Columbia according to the gravity model. Invasion into any one of these bodies of water will likely lead to an invasion into the Columbia. Similar conditions may exist for the Upper and Lower Colorado River Basins, which are less geographically isolated from dreissenid sources than the Columbia. The Great Basin already has a large number of boaters arriving from dreissenid sources, so policies in the Columbia are not expected to significantly change its probability of becoming invaded.

The affect of a quota on the probability of invasion into the Columbia is

$$\frac{d\varphi_C}{d\bar{n}} = \underbrace{\prod_w (1-q_{wC}\varphi_w)^{\frac{\bar{n}\; n_{wC,0}}{\sum_b n_{bC,0}}} \frac{d}{d\bar{n}}\left\{-(1-q_{EC})^{\frac{\bar{n}\; n_{EC,0}}{\sum_b n_{bC,0}}}\right\}}_{A} \underbrace{-(1-q_{EC})^{\frac{\bar{n}\; n_{EC,0}}{\sum_b n_{bC,0}}} \frac{d}{d\bar{n}}\left\{\prod_w (1-q_{wC}\varphi_w)^{\frac{\bar{n}\; n_{wC,0}}{\sum_b n_{bC,0}}}\right\}}_{B} \quad (7)$$

In general, the sign of expression (7) is ambiguous (a full derivation is in Appendix B). Part A shows how the quota affects the probability of an invasion from the East. Because higher quotas allow more boats and increase the probability of invasion from the East, Part A is positive. Part B traces the effect of the quota on probability of invasion from Western waters, i.e., the stepping stones effect. This effect depends on the change in probability of the other basins becoming invaded and the probability of invasion into the Columbia should these basins become invaded (see Appendix B). The stepping stone effect can be positive or negative, making the net effect of a quota in the Columbia River Basin on the probability of invasion into the Columbia is ambiguous.

Impacts due to quotas affect the region differently than technological changes due to a dreissenid invasion. The direct effect of quotas is to reduce demand from regional firms, reducing the demand for regional labor and capital. This already occurs at some level as visitor demand reacts to the added cost of angler services due to the increased cost of obtaining ecosystem services.

Figure 2 presents results across quota levels accounting with and without stepping stones. The ‘No Stepping Stones’ scenario shows the underestimation of damages caused by ignoring non-Eastern sources of risk ($q_{wC} = 0$); the ‘Stepping Stones’ scenario shows damages with full consideration of other sources of risk and substitutability.[††] All other assumptions were maintained between scenarios. Panel A shows changes in welfare relative to the full invasion scenario. We aggregated across households by weighting percentage change in welfare by share of total population represented by each household.[‡‡] Panel B shows probability of invasion, and panel C shows price and income indices.

In the presence of stepping stones, quotas cause welfare to fall below a full invasion for all but the strictest quotas. Low quota levels do little to reduce the probability of invasion, and reduced visitor spending causes region incomes to fall. Reduced demand also causes prices to fall, but not as quickly as incomes. Such policies can emerge when stepping stones are not addressed, which causes risk assessment to be biased downward and perceived effects of quotas to be come earlier. Assume welfare increases monotonically with the quota level.

With stepping stones, only for restrictions greater than 91 percent of the original number of boaters does welfare improve over a full invasion for all households. It is not until 90 percent of boaters are removed (allowing about 7,000 of the original 68,000 boats to enter) that the probability of invasion falls below 90 percent in the stepping stones scenario. In contrast, not considering stepping stones leads to an assumed probability of invasion of 68 percent without quotas. Stepping stones are currently the

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[††] The number of boaters from the East is small compared to the number of boaters that enter from the West, and visually one cannot distinguish between the results differentiated by the number of Eastern boaters that launch in other western basins. Figure 2 shows welfare losses and the probability of invasion when fifty percent of turned away Eastern boaters launch elsewhere in the West ($\Gamma = 0.5$)

[‡‡] Relative Impact = $\sum_h \left(V_h(\overline{P}^a, M_h^a) / V_h(\overline{P}^b, M_h^b) \times \text{(Households of type } h\text{/ Total Population)} \right)$, where V_h is indirect utility, M_h is income, benchmark b is without quotaa, and alternative a is with quotas.

main threat to the Columbia River Basin. Because a local quota policy cannot control launches in other western basins, it is virtually worthless.

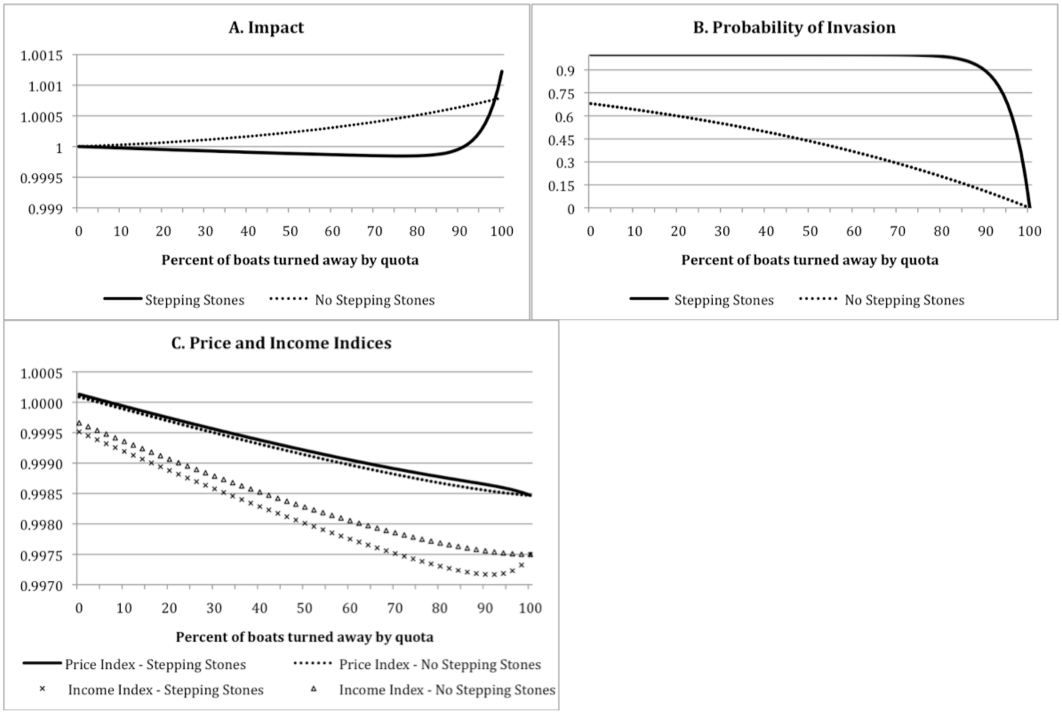

Figure 2. Comparison of impacts from quotas with and without stepping stones

Inspections: The effect of an inspection on the probability of an invasion into the Columbia River Basin is

$$\begin{aligned}\frac{d\varphi_C}{d\bar{I}} = {} & \prod_w (1-q_{wC}\varphi_w)^{n_{wC,0}-\bar{I}\frac{n_{bC}}{\sum_b n_{bC}}} \frac{d}{d\bar{I}}\left\{-(1-q_{EC})^{n_{EC,0}-\bar{I}\frac{n_{EC}}{\sum_b n_{bC}}}\right\} \\ & -(1-q_{EC})^{n_{EC,0}-\bar{I}\frac{n_{EC}}{\sum_b n_{bC}}} \frac{d}{d\bar{I}}\left\{\prod_w (1-q_{wC}\varphi_w)^{n_{wC,0}-\bar{I}\frac{n_{bC}}{\sum_b n_{bC}}}\right\}\end{aligned} \tag{8}$$

which is again ambiguous and derived in the appendix. The sign of the top line of equation (8) depends on the marginal effect of inspections on probability of invasion from the East. This term is negative, as the per boat probability and the number of boaters from the East are reduced. The sign of the bottom expression depends on the marginal effect on the probability of invasion with regard to western boaters. Inspections decrease the likelihood of an infected boat entering the Columbia River Basin, but because turned away boats from the East could decide to launch in the non-Columbia western basins, φ_w will rise.

This is a transfer in risk result for inspections and illustrates how risks may not be resolved; rather, they are just transferred through time and space (see e.g., Shogren and Crocker 1991). The net effect of an invasion with regards to sources in the West depends on the relative size of these two affects, as shown in (A.12), and is ambiguous. As in the quota case, equation (8) can be rearranged to show that inspections cause aggregate probability of an invasion to rise if the rate of change in probability of invasion from the West exceeds the rate of change of probability from the East. Inspections differ from quotas, however, according to the number of boats turned away that eventually launch in other waters. In our model, expected fines to any one boater are low, so substitution to other bodies of water is low, and probability of invasion into other basins is not drastically affected. Inspections, because they clean infected boats rather than direct them to other basins, reduce the probability of invasion in all basins and are likely to be more effective than quotas.

Figure 3 shows the results for an inspection policy. Policies that inspect less than 77 percent of boats cause welfare losses above those of a full invasion in the Stepping

Stones scenario. An inspection policy that ignores western threats, No Stepping Stones, is assumed to inspect only boats from the East. Western boaters continue to enter as before the policy. Figure 3 shows damages and probability of invasion are biased downward. Ignoring stepping stones leads one to believe inspections lead to immediate benefits, primarily through increased productivity of factors and higher incomes. By inspecting all Eastern boaters policymakers assume all losses are eliminated, though threats from the West keep invasion nearly certain and the true expected impacts near the full invasion level. Again, we see in the presence of stepping stones, policies focused only on known sources are of little use.

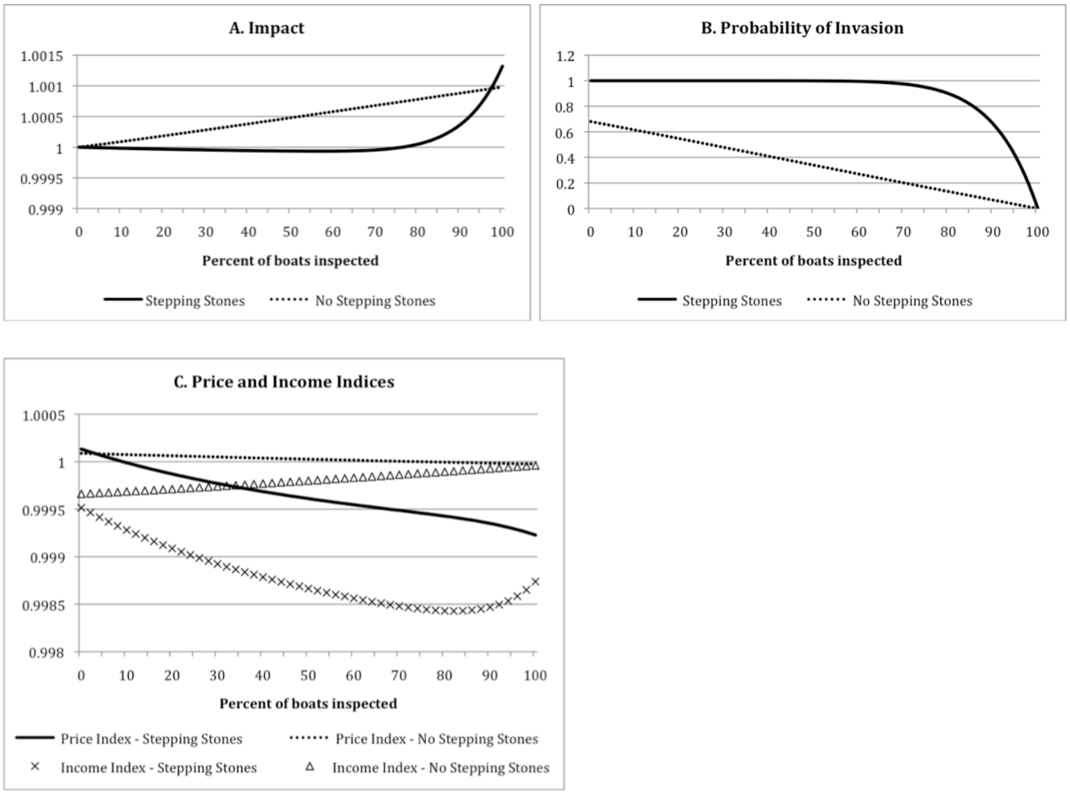

Figure 3. Comparison of impacts from inspections with and without stepping stones

An inspection policy, accounting for all sources of risk, has a number of advantages over quotas in the Columbia River Basin. First, because expected fines to any one boater are relatively small, the reduction in boaters, and visitor spending, is smaller with an inspection policy than with a quota. Second, while both policies have the ability to make the situation worse, the size of additional losses are smaller under an inspection policy. Third, inspections bring the probability of an invasion down quicker than a quota system. Inspecting every boat can remove the threat of invasion while allowing some visitors to enter the basin.

Sensitivity Analysis and Tipping Points:

In the Columbia River Basin, stepping stones are currently the greatest source of risk. The number of boats from other western basins overwhelms the number of boats from eastern dreissenid sources. Even small probabilities of invasion into the west imply almost certain invasion into the Columbia. This result depends on two parameters: the number of boats traveling to western basins ($n_{Ew,0}$) and the per boat probabilities of invasion (q_{EC}, q_{Ew}, and q_{wC}). A sensitivity analysis was performed on these parameters to see when policies imply an increase in risk and when the number of boaters from other boaters is too large to control.

The method assumes the per boat probability of invasion for each basin (q_{EC}, q_{Ew}, and q_{wC}) is distributed uniformly, centered on the estimated value (see Table 2) and bound by bound by half the estimated value and one and a half times the estimated probability of invasion, e.g., $q_{EC} \sim \mathrm{U}[0.5q_{EC,0},\ 1.5q_{EC,0}]$. Independent draws from all distributions define a scenario. For each scenario, we calculated the probability of invasion 1) without prevention policies, 2) with a 50 percent quota policy, and 3) with a

50 percent inspection policy. 500 such scenarios were generated, creating a distribution of impacts and probabilities for each policy. We repeated this process for incremental increases in the number of boaters originally traveling from the East to western basins ($n_{Ew,0}$). Figure 4 shows the resulting average probabilities of invasion for each scenario (Panel A) and the frequency each policy led to decreases in the probability of invasion (Panel B), across levels of $n_{Ew,0}$ from zero to 15 percent of its original value.

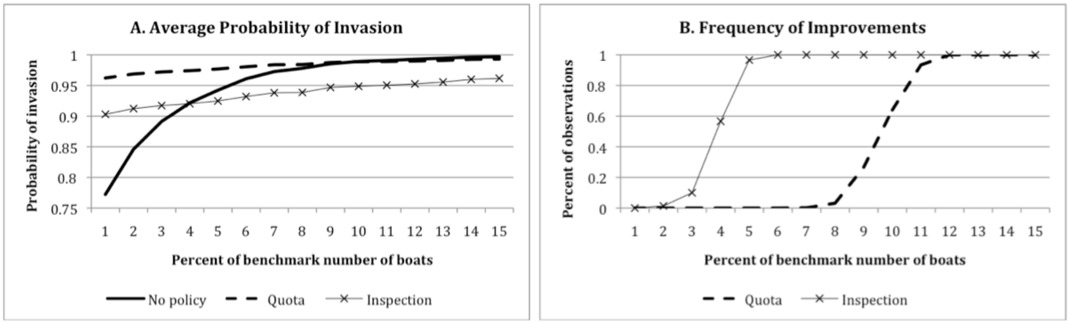

Figure 4. Influences on the number of boaters from East to West on the probability of invasion.

Figure 4 illustrates the results. When few boats visit the other western basins, both a 50 percent quota policy and a 50 percent inspection policy cause an increase in probability of invasion, as risk to the west is mostly from boats turned away from the Columbia. As the number of boaters visiting western boaters increases, the marginal effect of limiting boaters into the Columbia has little effect on probability of invasion into the western basins, and also has little effect on the probability of invasion into the Columbia. At 100 percent of the benchmark $n_{Ew,0}$, a 50 percent quota allows 1003 boats traveling from the East to enter the Columbia and 33,548 boats traveling from the West to enter the Columbia. 500 boats turned away from the Columbia launch into the West.

Compared to using no prevention policy, quotas increase the average probability of invasion for values of $n_{Ew,0}$ less than 10 percent of its original value, and inspections increase the average probability of invasion for values of $n_{Ew,0}$ less than 4 percent of its original value. This represents about 625 and 250 boats traveling from the East to Western waters. By 12 percent all quota draws led to decreases in risk over the no policy scenario, and by 6 percent all inspection draws led to decreases in risk over the no policy scenario. We find policies can be harmful, but only when few visitors are already traveling to western waters. At real world levels of boating, policies are not likely to increase the probability of invasion because, with stepping stones, probability is already near one.

4. Conclusion

Our bioeconomic model suggests the annual welfare losses of a dreissenid invasion in the Columbia River Basin could be \$64 million. Welfare losses in partial equilibrium analysis based on the same impact scenario are biased upwards, in this example by 37 percent. Summing up damages across industries, as done in partial equilibrium, does not address substitution possibilities that act as insurance measures within an economic system against catastrophes in one sector. Assumptions about substitutability across market and nonmarket goods matter, but to a much less extent. Halving the elasticity of substitution led to a 4.5 percent error and doubling the elasticity of substitution led to an 8.6 percent error.

Current prevention efforts decrease expected impacts only if we limit consideration to eastern sources of risk. Accounting for sources of risk in the West, current prevention efforts do little. New sources of risk overwhelm the threat from the East. We find policies to reduce risk of dreissenid invasion into the Columbia River

Basin may transfer risk of invasion to other river basins in the West. If these basins become invaded the outlook for the Columbia is even bleaker. Nearby infested waters can serve as stepping stones for eventual invasion into the Columbia River Basin. If the potential for invasion in the other western basins and the number of boats traveling between these basins and the Columbia are high, risk reduction policies will be counterproductive. Expected damages will rise.

Inspections outperform quotas and allow visitors to fish Columbia River Basin waters and reduce the probability of invasion quicker than quotas. Reducing the probability of invasion should be a priority because the damages of a dreissenid invasion are irreversible. A uniform effort between agencies of inspecting boats and installing wash stations at launch sites would reduce the probability of invasion per boat, and be more effective at reducing expected impacts than a decrease in the number of boats. Uniform efforts are particularly important due to the weak-link nature of maintaining ecosystem services. Lack of cooperation at any geographic or agency level can transfer the risk of invasion from one basin to another and do little to mitigate damages.

The oversight required to ensure compliance adds costs to anglers and government and raises the question of the ‘appropriate’ probability of invasion. The political will supporting these actions could increase, however, because the alternative is to impose significant costs on a few key industries, e.g., power and municipal water, and to increase the long term impacts of a dreissenid invasion on recreational water users and regional tourism. A full cost-benefit analysis would have to consider these administrative costs and the impact measures presented in this paper.

Appenix A. Full description of the model

Invasion	φ_C φ_w Φ_s PA_E Δ_s q_{xy}	Invasion probability into Columbia Invasion probability into western basins Expected damages parameter Implied price of ecosystem services Industry specific impact from invasion Invasion probability per boat from basin *x* into basin *y*	$\varphi_C = 1-(1-q_{EC})^{n_{EC}-I_E}\prod_w \left(1-q_{wC}\varphi_w\right)^{n_{wC}-I_w}$ $\varphi_w = 1-(1-q_{Ew})^{n_{Ew}}$ $\Phi_s = \varphi_C \times \Delta_s + (1-\varphi_C)$ $PA_E = \varphi_C(1+\Delta_E)+(1-\varphi_C)$
Policies	τ_b f n_{xy} XEE_b XE_s Γ I_b	Implied tax rate of boaters from *b* into Columbia Fine imposed on infested boats Number of boaters traveling from *x* to *y* Exports of angling from Columbia to region *b* Exports of good *s* Percent of boats switching from Columbia to West Number of boats inspected from basin *b*	$\tau_b = E_b[f] = f \times (I_b / n_{bC}) \times (q_{bC}\varphi_b)$ $XEE_b = quota \times \overline{XEE}_b\left(PA_{ANGLER}(1+\tau_E)\right)^{-\eta}$ $n_{bC} = XEE_b \dfrac{\overline{n}_{EC} + \sum_w n_{wC}}{\overline{XE}_{ANGLER}}$ $n_{Ew} = \overline{n}_{Ew} + \Gamma \times (\overline{n}_{EC} - n_{EC}) \times \overline{n}_{Ew} / \sum_b \overline{n}_{Ew}$ $\sum_b I_b = \dfrac{f}{P_I}\left(I_E q_{EC} + \sum_w I_w q_{wC}\varphi_w\right)$
Firm Behavior	DY_s CV_s VA_s V_{rs} L_s K_s $P_{va,s}$ PA_s W R α_{rs} ϕ_s δ_s σ_s τ_s	regional output of firm *s* costs to firm *s* value added for firm *s* Intermediate input *r* used by firm *s* Labor demand Capital demand CES composite price for value added Armington price for good *s* Wage rate Price of capital Leontief production parameter Production efficiency parameter Share of labor in production Elasticity of substitution in value added Tax rate on production of *s*	$DY_s = \min\{VA_a, \alpha_{1s}V_{1s}, .., \alpha_{rs}V_{rs}\}$ $CV_s = (P_{VA,s}VA_s + \sum_{r \neq s} PA_r V_{rs})(1+\tau_s)$ $VA = \Delta_s \phi_s^{-1}\left[\delta_s^{\sigma_s} L_s^{1-\sigma_s} + (1-\delta_s)^{\sigma_s} K_s^{1-\sigma_s}\right]^{1/(1-\sigma_s)}$ $V_{rs} = \alpha_{rs} DY_s$ $L_s = \left(DY_s \phi^{-1}\right)^{1-\sigma_s}\left(P_{VA}\delta_s / W\right)^{\sigma_s}$ $K_s = \left(DY_s \phi^{-1}\right)^{1-\sigma_s}\left(P_{VA}(1-\delta_s)/R\right)^{\sigma_s}$ $E[P_{VA,s}] = \Phi_s DY_s\left[\delta_s^{\sigma_s} W^{1-\sigma_s} + (1-\delta_s^{\sigma_s})R^{1-\sigma_s}\right]^{1/1-\sigma_s}$
Household Behavior	U_h $XH_{s,h}$ M_h MD_h PU_h $PA_{REC,h}$ $mpsd$ $mpsf$ θ_s ρ ρ_E ρ_C	Utility of household *h* Houshold demand Household income Household disposable income CES composite price of utility CES composite price for recreation Domestic savings rate Foreign savings rate Calibrated parameter for share of good *s* in utility Parameter related to elasticity of substitution Parameter for substitution in recreation Parameter for substitution in consumption goods	$U_h(XH,E) = \left[\theta_{REC}\left(\theta_E E^{\rho_E} + (1-\theta_E)XH_A^{\rho_E}\right)^{\rho/\rho_E} + (1-\theta_{REC})\left(\sum_{s \neq R,A}\theta_s XH_s^{\rho_C}\right)^{\rho/\rho_C}\right]^{1/\rho}$ $XH_{s \neq A,E} = \overline{XH}_s \dfrac{MD_h}{\overline{MD}_h PU_h}\left(\dfrac{PU_h \overline{PA}_s}{PA_s}\right)^{\sigma_h}$ $XH_{r=A,E} = \overline{XH}_{r,h} \dfrac{XH_{REC,h}}{\overline{XH}_{REC,h} PA_{REC,h}}\left(\dfrac{PA_{REC,h}\overline{PA}_r}{PA_r}\right)^{\sigma_{Eh}}$
Income	M_h MD_h $LABPMT$ $CAPPMT$ $INTINC_h$ $EXINT_h$ $TRN_{x,y}$ $\tau_{x,g}$ $LRENT\ KRENT$ $LOUT$ $KOUT$	Income of household *h* Disposable income of household *h* Total payments to labor Total payments to capital Interest income to household h Income from outside the region Transfers from *x* to *y* Tax rate paid from *x* to government *g* Rents to labor Rents to capital Labor payments out of region Capital payments out of region	$M_h = \theta_h^L LABPMT + \theta_h^K CAPPMT + \overline{TRN}_{FED,h} + \overline{TRN}_{STATE,h} + \overline{EXINC}_h$ $+ INTINC_h$ $MD_h = M_h(1-\tau_{h,FED} - \tau_{h,STATE} - mpsd - mpsf) + PA_E XH_{h,E}$ $INTINC_h = \theta_h^{INT}\left(\begin{array}{l}\sum_s QINV_s PA_s + LRNT + KRENT + \sum_h mps_h^d M_h \\ + \overline{TRN}_{FED,CORP} + \overline{TRN}_{STATE,CORP} + \overline{IINT} + EXOSAV\end{array}\right)$ $LABPMT = (\sum_s L_s W - LRENT - \overline{LOUT})(1-\tau_{L,FED} - \tau_{L,STATE})$ $CAPPMT = (\sum_s K_s R - KRENT - \overline{KOUT})(1-\tau_K^{FED} - \tau_K^{STATE})$

Government	$GREV_g$ $XG_{g,s}$ $QG_{g,s}$ $ENTAX_g$ PD_s $\gamma_{g,s}$ $\gamma_{s,g}$ $\alpha_{s,g}$ IT_s $IINT$ $IEXINT$ $QINV_s$	Government revenue Government demand Government supply Enterprice tax collected by government *g* Domestic price for good *s* Share of business taxes to government *g* Government demand is fixed portion of revenue Government supply is fixed portion of output Investment undertaken by firm *s* Inventory additions to retained earnings Interest paid out of region Inventory of good *s*	$GREV_g = \sum_s QG_{s,g} PD_s + \tau_{L,g}(\sum_s L_s W - LRENT - \overline{LO}\,\overline{UT})$ $+\tau_{K,g}(\sum_s K_s R - KRENT - \overline{KO}\,\overline{UT})$ $+\gamma_{g,s}(\sum_s CV_s \tau_s) + \sum_h \left(MD_h \tau_{h,g} - TRN_{g,h}\right) + ENTAX_g - \overline{TR}\,\overline{N}_{g,OTHER}$ $XG_{s,g} = \gamma_{s,g} GREV_g$ $QG_{s,g} = \alpha_{s,g} DY_s$ $ENTAX_g = \tau_{ENT,g}(\sum_h INTINC_h + \sum_s IT_s + \sum_g ENTAX_g + \overline{II}\,\overline{NT} + IEXINT)$ $QINV_s = \alpha_{INV,s} DY_s$ $IT_s = \alpha_{IT,s} DY_s$
Trade	AC_s arm_s $QIMP_s$ QD_s XD_s Q_s X_s AT_s g_s XE_s $\sigma_{arm,s}$ $\rho_{arm,s}$ $\sigma_{ROW,s}$ $\rho_{ROW,s}$	Armington coefficient Share of imports in benchmark supply Imports of good *s* Domestic supply of good *s* Domestic demand of good *s* Total supply of good *s* Total demand of good *s* Export coefficient Share of exports in benchmark demand Exports of good *s* Elasticity of substitution for imports Import elasticity parameter Elasticity of substitution for exports Export elasticity parameter	$Q_s = AC_s\left(arm_s QIMP_s^{\rho_{arm,s}} + (1 - arm_s) QD_s^{\rho_{arm,s}}\right)^{1/\rho_{arm,s}}$ $\frac{QD_s}{QIMP_s} = \left(\frac{1 - arm_s}{arm_s} \frac{PM_s}{PD_s}\right)^{\sigma_{arm,s}}$ $X_s = AT_s\left(g_s XE_s^{\rho_{s,ROW}} + (1 - g_s) XD_s^{\rho_{s,ROW}}\right)^{1/\rho_{s,ROW}}$ $\frac{XD_s}{XE_s} = \left(\frac{1 - g_s}{g_s} \frac{PM_s}{PD_s}\right)^{\sigma_{t,s}}$
Markets	$\overline{L}$ $\overline{K}$	Total labor endowment Total capital endowment	$QD_s = DY_s + QG_{FED,s} + QG_{STATE,s} + QINV_s$ $XD_s = \sum_{r \neq s} V_{rs} + \sum_h x_{hs} + XG_{s,FED} + XG_{s,STATE} + IT_s$ $PA_s Q_s = PD_s QD_s + PM_s QIMP_s$ $X_s = Q_s$ $\overline{K} = \sum_s K_s$ $\overline{L} = \sum_s L_s$ $CV_s = PD_s DY_s$
Closure	$EXOSAV$ BRW_g	Exogenous savings Borrowing by government *g*	$IEXINT = \sum_s XE_s PX_s + \sum_h HEXINC_h + \sum_g BRW_g + EXOSAV$ $-\sum_s QIMP_s PM_s - \sum_f FACOUT_f - \sum_h FORSAV_h - STTRND - FDTRND$ $EXOSAV = IEXINT + \sum_s IT_s PD_s + \sum_h HHINTINC_h + FENTAX + SENTAX + IIN$ $-\sum_s QINV_s - LRNT - KRNT - \sum_h REGSAV_h - FDTRNCRP$ $-STTRNCRP - IINT$ $BRW_g = \sum_s XG_{s,g} PA_s + \sum_h TRNS_{g,h} + \overline{TR}\,\overline{N}_{g,OTHER} - GREV_g$

Appendix B. Marginal changes in probability

B.1 Probability of invasion with a quota

Let $\bar{n}$ be the total number of boats allowed into the Columbia River Basin. The numbers of boaters from each basin continue to arrive in equal proportions as they did prior to the invasion, given by equation (3). Equation (4) gives the number of boats from the East that now travel to other basins in the West.

With the quota probability of invasion is

$$\varphi_C(\bar{n}|Z_c) = 1-(1-q_{EC})^{\frac{\bar{n}\, n_{EC,0}}{\sum_j n_{jC,0}}} \prod_i (1-q_{iC}\varphi_i)^{\frac{\bar{n}\, n_{iC,0}}{\sum_j n_{jC,0}}} \quad \text{for } i,j = Ca, G, Pa, U, L, \text{ and } R. \tag{A.1}$$

Taking the derivative with respect to the quota level

$$\frac{d\varphi_C}{d\bar{n}} = \prod_i (1-q_{iC}\varphi_i)^{\frac{\bar{n}\, n_{iC,0}}{\sum_j n_{jC,0}}} \frac{d}{d\bar{n}}\left\{-(1-q_{EC})^{\frac{\bar{n}\, n_{EC,0}}{\sum_j n_{jC,0}}}\right\} - (1-q_{EC})^{\frac{\bar{n}\, n_{EC,0}}{\sum_j n_{jC,0}}} \frac{d}{d\bar{n}}\left\{\prod_i (1-q_{iC}\varphi_i)^{\frac{\bar{n}\, n_{iC,0}}{\sum_j n_{jC,0}}}\right\} \tag{A.2}$$

The marginal change on the probability from boaters from the East in unambiguously positive,

$$\frac{d}{d\bar{n}}\left\{-(1-q_{EC})^{\frac{\bar{n}\, n_{EC,0}}{\sum_j n_{jC,0}}}\right\} = -\frac{n_{EC,0}}{\sum_j n_{jC,0}} \cdot \ln(1-q_{EC}) \cdot (1-q_{EC})^{\frac{\bar{n}\, n_{EC,0}}{\sum_j n_{jC,0}}} > 0 \tag{A.3}$$

The marginal change on probability for other boaters is

$$\begin{aligned}\frac{d}{d\bar{n}}\left\{\prod_i (1-q_{iC}\varphi_i)^{\frac{\bar{n}\;n_{iC,0}}{\sum_j n_{jC,0}}}\right\} &= (1-q_{1C}\varphi_1)^{\frac{\bar{n}\;n_{1C,0}}{\sum_j n_{jC,0}}}\frac{d}{d\bar{n}}\left\{\prod_{i\neq 1}(1-q_{iC}\varphi_i)^{\frac{\bar{n}\;n_{iC,0}}{\sum_j n_{jC,0}}}\right\} \\ &\quad +\prod_{i\neq 1}(1-q_{iC}\varphi_i)^{\frac{\bar{n}\;n_{iC,0}}{\sum_j n_{jC,0}}}\frac{d}{d\bar{n}}\left\{(1-q_{1C}\varphi_1)^{\frac{\bar{n}\;n_{1C,0}}{\sum_j n_{jC,0}}}\right\}\end{aligned} \tag{A.4}$$

Note that $\frac{d}{dx}\left\{f(x)^{g(x)}\right\} = f(x)^{g(x)-1}g(x)f'(x) + f(x)^{g(x)}g'(x)\ln(f(x))$, which we use to get

$$\begin{aligned}\frac{d}{d\bar{n}}\left\{(1-q_{1C}\varphi_1)^{\frac{\bar{n}\;n_{1C,0}}{\sum_j n_{jC,0}}}\right\} &= (1-q_{1C}\varphi_1)^{\frac{\bar{n}\;n_{1C,0}}{\sum_j n_{jC,0}}-1}\cdot\frac{\bar{n}\;n_{1C,0}}{\sum_j n_{jC,0}}\cdot\left(-q_{1C}\frac{d}{d\bar{n}}\{\varphi_1\}\right) \\ &\quad +(1-q_{1C}\varphi_1)^{\frac{\bar{n}\;n_{1C,0}}{\sum_j n_{jC,0}}}\cdot\frac{n_{1C,0}}{\sum_j n_{jC,0}}\cdot\ln(1-q_{1C}\varphi_1)\end{aligned} \tag{A.5}$$

Raising the quota in the Columbia River Basin keeps fewer boats from infested areas in the East from entering other basins in the West, decreasing the probability that they become invaded, $\frac{d}{d\bar{n}}\{\varphi_1\} < 0$. The first term is positive. Because $1-q_{1C}\varphi_1 < 1$, the second term is negative. The sign of the whole term is ambiguous, which implies equation (A.2) is ambiguous as well.

B.2 Probability of invasion with inspections

The probability of an invasion with an inspection policy is given by equation (5), which can be written in terms of total inspections,

$$\varphi_C(\bar{I}|Z_c) = 1-(1-q_{EC})^{n_{EC,0}-\bar{I}\frac{n_{EC}}{\sum_b n_{bC}}}\prod_w (1-q_{wC}\varphi_w)^{n_{wC,0}-\bar{I}\frac{n_{bC}}{\sum_b n_{bC}}} \tag{A.6}$$

Taking the derivative with respect to the inspection level

$$\begin{aligned}\frac{d\varphi_C}{d\bar{I}} &= -(1-q_{EC})^{n_{EC,0}-\bar{I}\frac{n_{EC}}{\sum_b n_{bC}}}\frac{d}{d\bar{I}}\left\{\prod_w (1-q_{wC}\varphi_w)^{n_{wC,0}-\bar{I}\frac{n_{bC}}{\sum_b n_{bC}}}\right\} \\ &\quad +\prod_w (1-q_{wC}\varphi_w)^{n_{wC,0}-\bar{I}\frac{n_{bC}}{\sum_b n_{bC}}}\frac{d}{d\bar{I}}\left\{-(1-q_{EC})^{n_{EC,0}-\bar{I}\frac{n_{EC}}{\sum_b n_{bC}}}\right\}\end{aligned} \tag{A.7}$$

The bottom term depends on the effect of inspections on the probability of invasion from the East and is negative. Higher inspection rates lower the probability of invasion from the East.

$$\frac{d}{d\bar{I}}\left\{-(1-q_{EC})^{n_{EC,0}-\bar{I}\frac{n_{EC}}{\sum_b n_{bC}}}\right\} = \left(-\frac{n_{EC}}{\sum_b n_{bC}}\right)\ln(1-q_{EC})\cdot(1-q_{EC})^{n_{EC,0}-\bar{I}\frac{n_{EC}}{\sum_b n_{bC}}} < 0 \tag{A.8}$$

The top term of (A.7) depends on the effect of inspections on the probability of invasion from the West

$$\begin{aligned}\frac{d}{d\bar{I}}\left\{\prod_w (1-q_{wC}\varphi_w)^{n_{wC,0}-\bar{I}\frac{n_{wC}}{\sum_b n_{bC}}}\right\} &= (1-q_{1C}\varphi_1)^{n_{1C,0}-\bar{I}\frac{n_{1C}}{\sum_b n_{bC}}}\frac{d}{d\bar{I}}\prod_{w\neq 1}(1-q_{wC}\varphi_w)^{n_{wC,0}-\bar{I}\frac{n_{wC}}{\sum_b n_{bC}}} \\ &\quad +\prod_{w\neq 1}(1-q_{wC}\varphi_w)^{n_{wC,0}-\bar{I}\frac{n_{wC}}{\sum_b n_{bC}}}\frac{d}{d\bar{I}}\left\{(1-q_{1C}\varphi_1)^{n_{1C,0}-\bar{I}\frac{n_{1C}}{\sum_b n_{bC}}}\right\}\end{aligned} \tag{A.9}$$

Looking at the effect of inspections on probability of invasion from a representative basin,

$$\frac{d}{d\bar{I}}\left\{(1-q_{1C}\varphi_1)^{n_{1C,0}-\bar{I}\frac{n_{1C}}{\sum_b n_{bC}}}\right\} = (1-q_{1C}\varphi_1)^{n_{1C,0}-\bar{I}\frac{n_{1C}}{\sum_b n_{bC}}-1}\left(n_{1C,0}-\bar{I}\frac{n_{1C}}{\sum_b n_{bC}}\right)(-q_{1C}\frac{d}{\bar{I}}\{\varphi_1\})$$
$$+(1-q_{1C}\varphi_1)^{n_{1C,0}-\bar{I}\frac{n_{1C}}{\sum_b n_{bC}}}\left(-\frac{n_{1C}}{\sum_b n_{bC}}\right)\ln(1-q_{1C}\varphi_1) \quad \text{(A.10)}$$

$\frac{d}{d\bar{I}}\{\varphi_1\} > 0$, so the first term will be negative. The second term will be positive because $\ln(1-q_{1C}\varphi_1) < 0$. Once again, the net effect on the probability will be ambiguous depending on the tradeoff between reducing the per boat probability and increasing the probability that a given western basin becomes infected.

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