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Implications for U.S. Trade and Nonindigenous Species Risk Resulting from Increased Economic Integration of the Asia-Pacific Region

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ABSTRACT
This work investigates how potential changes in trade patterns resulting from increased economic integration in the Asia-Pacific region may affect the risk for nonindigenous species spread to the United States. We construct an invasion risk index utilizing the results from a global economic modeling framework in tandem with data for climate similarities between trade partners. The index is based on risk of introduction, determined by changes in trade, and risk of establishment, given by terrestrial and marine climate similarities between countries. The results indicate that Japan may be the riskiest trade partner for the United States in the Asia-Pacific region from a nonindigenous species perspective. This is driven by large expected changes in trade and high environmental similarity between the two countries. This research provides the basis of a risk assessment prediction system to examine the effects of changes in trade on nonindigenous species risk, an important, novel contribution to the trade policy literature.

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Introduction

This paper examines the effects of freer trade on the risk of nonindigenous species (NIS) spread. Specifically, we assess the impact of reductions in trade frictions between the United States and countries in the Asia-Pacific region on invasion risk to the U.S. Trade between the United States and partners in Asia gained prominence during the 2017 U.S. presidential election, especially with regard to U.S. involvement in the Trans-Pacific Partnership (TPP) negotiations. The TPP would have been a preferential trade and investment agreement among 12 Pacific Rim countries[1] targeted to increase economic activity between member nations (Fergusson, McMinimy, and Williams 2015). Together, the 12 countries involved in the original TPP negotiations make up nearly 1% of the global population and approximately 40% of global gross domestic product (GDP) (Burfisher et al. 2014). Implementation required ratification by six countries, comprising 85% of member GDP. Essentially, this meant that the agreement would only enter into effect if ratified by the United States and failed when the United States chose not to ratify the pact.

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Despite the failure of TPP, the United States continues to stress the importance of trade on the economy and seeks ways to increase trade with the Asia-Pacific region. For example, the formation of a new undersecretary for international trade within the U.S. Department of Agriculture has been proposed, and current Secretary of Agriculture Sonny Perdue called for more data informed trade strategies during one of his first official addresses. As the United States seeks to expand trade with both historic and emerging trade partners, it is important to understand the implications for NIS risk. Trade agreements increase trade between partners by both increasing the absolute volume of traded goods and by diverting trade away from nonagreement countries, which have direct effects on NIS spread. Burfisher et al. (2014) found that freer trade between Pacific Rim countries would cause agricultural imports and exports to increase for every participating country, with Japan and the United States accounting for a large portion of new trade. (Burfisher et al. 2014).

These changes in trade are expected to spread NIS at rates and distances well beyond what would occur naturally (Blakeslee et al. 2010). NIS already established in the United States reflect the country's historical roots in trade and cultural exchange (Brawley et al. 2009). Europe is the source of most established species in the United States because it is the region with the oldest trade relationship with North America and also because the climate and vegetation are relatively similar (Niemela and Mattson 1996; Levine and D'Antonio 2003; Westphal et al 2008; Langor, DeHaas, and Foottit 2009). However, new pests such as the Asian long-horned beetle, emerald ash borer, and redbay ambrosia beetle have arrived from Asia, Central America, and South America coincident with increased trade from those regions (Haack et al. 1997; Siegert et al. 2007; Koch and Smith 2008).

Intentional introductions by nurseries, botanical gardens, and private plant enthusiasts have been responsible for most terrestrial introductions into the United States (Reichard and White 2001). This trend is shifting, however, as there is greater awareness of the harmful effects NIS can have on the environment (Sailer 1983; Aukema et al. 2010). Policy attention now focuses on unintentionally introduced species called "hitchhikers" that arrive in trade and transportation vectors (Molnar et al. 2008; Bain et al. 2010; Kaluza et al. 2010; Yemshanov et al. 2013). For example, herbaceous invasive species often arrive through crop seed contamination; aquatic species often arrive due to biofouling (accumulation of species on ship surfaces) and through ship ballast water exchange (Baker 1986, Drake and Lodge 2004, 2007, Perrins et al. 2006, Costello, Drake, and Lodge 2007; Hulme 2009, Keller et al. 2011, Seebens, Gastner, and Blasius 2013, Seebens et al. 2016); and wood-boring insects often spread through wood packaging materials (McNeely et al. 2001, IPPC 2002, Aukema et al. 2010) and movement of fuel wood (Liebhold and Tobin 2008; Jacobi, Goodrich, and Cleaver 2011; Koch et al. 2012; Barlow et al. 2014).

As discussed by Aukema et al. (2010), trade of a given commodity with a given trading partner is like a statistics exercise in repeated sampling. The probability of introduction of species linked to that vector increases with time, but the pool of potential new invaders associated with that vector decreases with time. Expanding trade with new partners for new commodities expands that pool of potential invaders. This effect may explain why European species account for the majority of established species, but Asian species account for the majority of recent introductions. Given that there are substantial barriers to trade between the United States and many Asian countries, removing these barriers would likely increase the risk for NIS spread.

Costello, Drake, and Lodge (2007) estimate that NIS cost from $4.7 billion to $136 billion annually in the United States. Pimentel, Zuniga, and, Morrison (2005) put this estimate at $120 billion annually. The U.S. Government Accountability Office (GOA) estimated that the federal government spent more than $500 million dollars in 1999 and 2000 for activities related to invasive species (GOA 2000). Florida spent $127.6 million on invasive species activities in 2000 (GOA 2000), and the Great Lakes states spend about $20 million every year just to control sea lamprey (Great Lakes 2012). In general, the costs of control and associated damages fall disproportionately on a few economic sectors and households. For example, the Russian wheat aphid primarily impacts wheat and barley producers, causing an estimated $850 million in direct and indirect losses from 1987 to 1992 (Brooks et al. 1994). During the 1992 to 1993 cropping season, approximately 20% of dryland winter wheat and 33% of barley throughout the western United States were infested by the Russian wheat aphid (Webster and Amosson 1994). Damages from West Nile Virus exceeded $4 million in the equine industries in Colorado and Nebraska (APHIS 2003) and led to more than $20 million in public health impacts in Louisiana (Zohrabian et al. 2004). Zebra mussels cause $300–$500 million annually in damages in the Great Lakes region (Great Lakes 2012) and could cause another $64 million in damages annually if they spread to the Columbia River basin (Warziniack, Finnoff, and Shogren 2013).

Others have addressed the environmental impacts of trade agreements and have found that increased trade can lead to increased pollution and lower environmental quality (Copeland and Taylor 1994, 1995, 2004; Antweiler, Copeland, and Taylor 2001). Other work shows that the environmental impacts of free trade agreements may be more ambiguous and suggests that developing economies may be most vulnerable to NIS spread, given lower economic integration (Grossman and Krueger 1994; Thuiller et al. 2005). These findings prompted the inclusion of enforceable commitments within newly negotiated trade agreements covering environmental standards related to pollution, wildlife, forestry, fisheries and marine ecosystems, terrestrial habitat, and biodiversity (U.S. Trade Representative 2015). The potential for trade to spread NIS, however, is different from the aforementioned environmental problems because risk comes from the vector itself, which limits the effectiveness of corrective policies (Warziniack et al. 2011). Others have assessed the role of inspections and quotas on limiting the spread of invasive species (Costello and McAusland 2003; Work et al. 2005; Keller et al. 2011), but by and large, results show that it is impossible to completely eliminate NIS risk.

We focus on the effect of trade expansion between the United States and Asia on the risk of species invasions, where risk of invasion depends on both the introduction of new species and the potential for those species to become established. We assume risk of introduction is positively correlated with changes in trade volume, measured by percentage changes in U.S. imports, and risk of establishment is positively correlated with climate similarities between countries. These measures of risk are discussed in greater detail in the next section. We then present the results of our analysis for changes in the potential risk for NIS spread, given changes in trade patterns and environmental similarity, which provides conclusions for the NIS risk that the United States may face with increased trade with Asia, or the risk that may be avoided if further economic integration does not occur.

Data and Methods

We divide the invasion process into two independent components: introduction and establishment conditional on being introduced. This method combines ecological niche models, which determine the potential range of a species, with spread models, which determine the likelihood a species will be introduced to a given location (Thuiller et al. 2005). As discussed by Seebens, Gastner, and Blasius (2013), NIS introduction and establishment can be treated as two independent random events, allowing a suitable risk index R_{ij} for commodity i from country j to be defined by the product of an index measuring the likelihood of introduction and an index measuring the likelihood of establishment. Several candidates for such measures have been proposed. For example, ballast discharge is mapped into a probability distribution for introductions (Seebens, Gastner, and Blasius 2013). Our intent in this paper is not to identify absolute probabilities of invasion, but rather to identify relative risk associated with current and projected trade expansion. We use the percentage change in trade volume as our measure of likelihood of introduction and a measure of climate similarities as our measure of likelihood of establishment. Let ΔT_{ij} denote the percentage change in imports of commodity i to the United States from country j. Let C_j denote the similarity of the climate in country j with the climate in the United States. Our measure of relative risk is described by

$$R_{ij} = \Delta T_{ij} \times C_j \tag{1}$$

We describe each component in turn.

Risk of Introduction—Changes in Trade

In the ecology literature, introductions are typically modeled as a function of geographic distance (gravity models) or as a function of connections along a network. Bossenbroek, Kraft, and Nekola (2001), for example, use a gravity model to predict long distance dispersal of zebra mussels in northern U.S. lakes based on distance from established populations and attractiveness of destination lakes to recreational boaters. Geographic distance likely captures the importance of North American trade partners such as Mexico and Canada but underestimates the role of long-established trade relations with Western Europe. Instead of geographic distance, others have used transportation networks and shipping patterns (Keller et al. 2011, Xu et al. 2014) and ballast water discharge (Seebens, Gastner, and Blasius 2013) to predict dispersal. A few studies model introductions as a function of trade volume (e.g., Early et al. 2016, Paini et al. 2016). This focus on trade as the driver of introductions, rather than geographic distance, number of ships, or ballast water, has the advantage of more closely linking invasions with the economic variable of interest. This approach also allows for better policy analysis and allows risk to be assessed for both marine and terrestrial invasions, given changes in trade. Two key insights from the literature are that the marginal risk from established trade partners is likely to be lower and that rates of introduction will increase from trade partners with a relatively shorter history of economic integration with the United States (Aukema et al. 2010).

Changes in trade are taken from Burfisher et al.'s (2014) study, who use the global trade analysis project (GTAP) model and GTAPv.8 database to examine the potential effects of trade liberalization in the Pacific Rim, embodied in the now defunct Trans-Pacific Partnership. The GTAP model and database have been widely used and cited in the economic literature, represent the structural features of interactions between multiple agents and sectors internationally, and provide a framework to assess economic shocks to the global economy (Hertel 1997, 2013). Burfisher et al.'s (2014) aggregation includes 12 countries (11 TPP members, excluding Brunei, and including the Rest of the World), 29 economic sectors, focusing heavily on agriculture, and natural resources (Table A1). Agricultural products are likely to be the most affected by further trade liberalization, given expected increases in market access for agricultural products (Burfisher et al. 2014).

Total demand for consumption goods in the United States is modeled by a two-stage, nested Armington structure common in the international trade literature to account for product differentiation by source (Armington 1969). First, demand shares for goods produced domestically and demand for aggregate imports are determined using constant elasticity of substitution (CES) preferences. In the second stage, aggregate imports are determined by total demand for imports by source region (Figure A1).

Aggregate imports into the United States (TA) for good i are a function of domestic market prices (PD) and the price for the composite import bundle (PMT) plus an *ad valorem* tax wedge (τ) and Armington elasticities (σ^{m}) that determine preferences for foreign versus domestically produced goods as shown in Equation 2.

$$\mathrm{TA}_i = f(\mathrm{PD}_i, \mathrm{PMT}_i, \tau_i, \sigma_i^{\mathrm{m}}) \tag{2}$$

The second stage of the Armington import demand specification determines imports (T) of commodity i by country of origin j and is a function of relative prices between import sources (PT), bilateral *ad valorem* tariffs (τ), and Armington elasticities (σ^{w}) that account for preferences between import sources, described by Equation 3.

$$T_{i,j} = f(\mathrm{PT}_{i,j}, \tau_{i,j}, \sigma_{i,j}^{\mathrm{w}}) \tag{3}$$

Given demand functions, zero profit conditions, and market clearing conditions, the model is solved to determine the changes in relative prices and changes in aggregate imports, giving ΔT_{ij} in Equation 1 as the percentage change in imports from country j for commodity i. In general, a key objective of trade agreements is to reduce the tax wedge that decreases both the price of the composite import and the relative prices between import sources. This leads to increased imports and exports between partner countries as relative price change. We present greater detail for the relevant behavioral equations used to derive changes in bilateral trade by commodity as Supplemental Material. The global economic model is fully described by Hertel (1997 and 2013) as well as by Van der Mensbrugghe and Mensbrugghe (2015), with a convenient graphical presentation of the model provided by Brockmeier (2001), and model-specific parameterization and scenario design described in detail by Burfisher et al. (2014).

Burfisher et al. (2014) updates the GTAPv8 database to the year 2014 and then projects it to 2025 given economic projections for endowments, population, and real GDP. Preferential trade agreements and unilateral tariff reductions currently scheduled out to 2025 are also included. These projections serve as the baseline, on which tariff eliminations consistent with the originally proposed TPP are modeled. This allows a comparison between 2025 member economies with and without TPP. For the purposes of this analysis, we focus our attention on the expected changes in U.S. imports from each TPP partner to assess the potential for species introduction.

Because our focus is on risk of species introductions rather than sectoral changes in trade, we aggregate the results for changes in U.S. imports from Burfisher et al.'s 29 economic sectors into 10 sectors (Table 2 and Table A1). We aggregated first by grouping GTAP agricultural sectors into similar growing areas in the United States and other sectors by primary means of shipping, while keeping sectors disaggregated enough to see primary changes by trading partner. We then calculated weighted average changes in U.S. imports for each aggregated sector by multiplying the percentage change in imports by the weight of total import value for that sector. This aggregation allows us to focus on the key sources of risk rather than the details of specific changes in trade by commodity. We do not account for risk management and prevention actions; therefore, our results imply upper bounds for risk. With limited resources available for NIS prevention, this work provides important insights into not only risky trade partners but types of merchandise trade that may be most important to target for monitoring.

Risk of Establishment—Climate Similarities

We based risk of species establishment on similarities between the climate of locations where species are known to occur and locations where species may be introduced. Climate is fundamental for species survival, and climate similarity between origin and introduced locations has been found to be the strongest predictor of NIS establishment across a wide variety of taxa (Bomford et al. 2009, Bacon et al. 2014, Howeth et al. 2016). In addition, climate matching has been used extensively to project potential habitats for non-native species (e.g., Thuiller et al. 2005, Bomford et al., 2009; Britton et al., 2010; Kopecký, Kalous, and Patoka 2013; Kalous, Patoka, and Kopecký 2015; Paini et al 2016, Seebens et al. 2016). While a variety of other factors specific to introduction events, introduction locations, or species have been linked to establishment success, we focus on climate matching because of its general applicability and because climate data are readily available at a global scale. This study does not consider NIS spread, which is often best predicted by time since introduction (Allen et al. 2013, Byers et al. 2015) or species traits (Kolar and Lodge 2002, Higgins and Richardson 2014), but climate matching has been found to play a role in these risks, as well (Kulhanek, Leung, and Ricciardi 2011, Iacarella et al. 2015, Howeth et al. 2016).

Our measure of climate similarity is based on Euclidean distance between 16 climate variables for terrestrial matching and 4 surface water variables for marine matching (Table 1). For terrestrial matching, the climate variables were obtained from 552 meteorological stations in the destination country (the United States) and from each source country from the Worldclim Version 2 database (Fick and Hijmans 2017). If fewer stations were available in the source country, the maximum number of stations was used. For marine climate matching, data for ports in both destination ($N = 552$) and source countries ($N = 552$ or maximum number of source ports) were obtained from Keller et al.'s (2011) study. Both terrestrial and marine climate matching were completed in R (R Core

Table 1. Terrestrial and marine Climatch variables.

Climatch variables	
Mean annual temperature	Mean annual precipitation
Minimum temperature of coolest month	Mean precipitation of wettest month
Maximum temperature of coolest month	Mean precipitation of driest month
Average temperature range	Mean monthly precipitation coefficient of variation
Mean temperature of coolest quarter	Mean precipitation of coolest quarter
Mean temperature of warmest quarter	Mean precipitation of warmest quarter
Mean temperature of wettest quarter	Mean precipitation of wettest quarter
Mean temperature of driest quarter	Mean precipitation of driest quarter
Marine match variables	
Minimum temperature	Yearly mean temperature
Maximum temperature	Salinity of all surface waters

Sources: Crombie et al. 2008 and Keller et al. 2011.

Team 2014) using an algorithm similar to the closest Euclidean Match algorithm employed by the Australian government's Climatch software (Crombie et al. 2008). The lowest Euclidean distance, in 16-variable space (terrestrial matching) or 4-variable space (marine matching), was calculated for each U.S. and source meteorological station, or port, indicated by the colored "dots" on the maps included in Figure 1. The Euclidean distance is defined in equation 4.

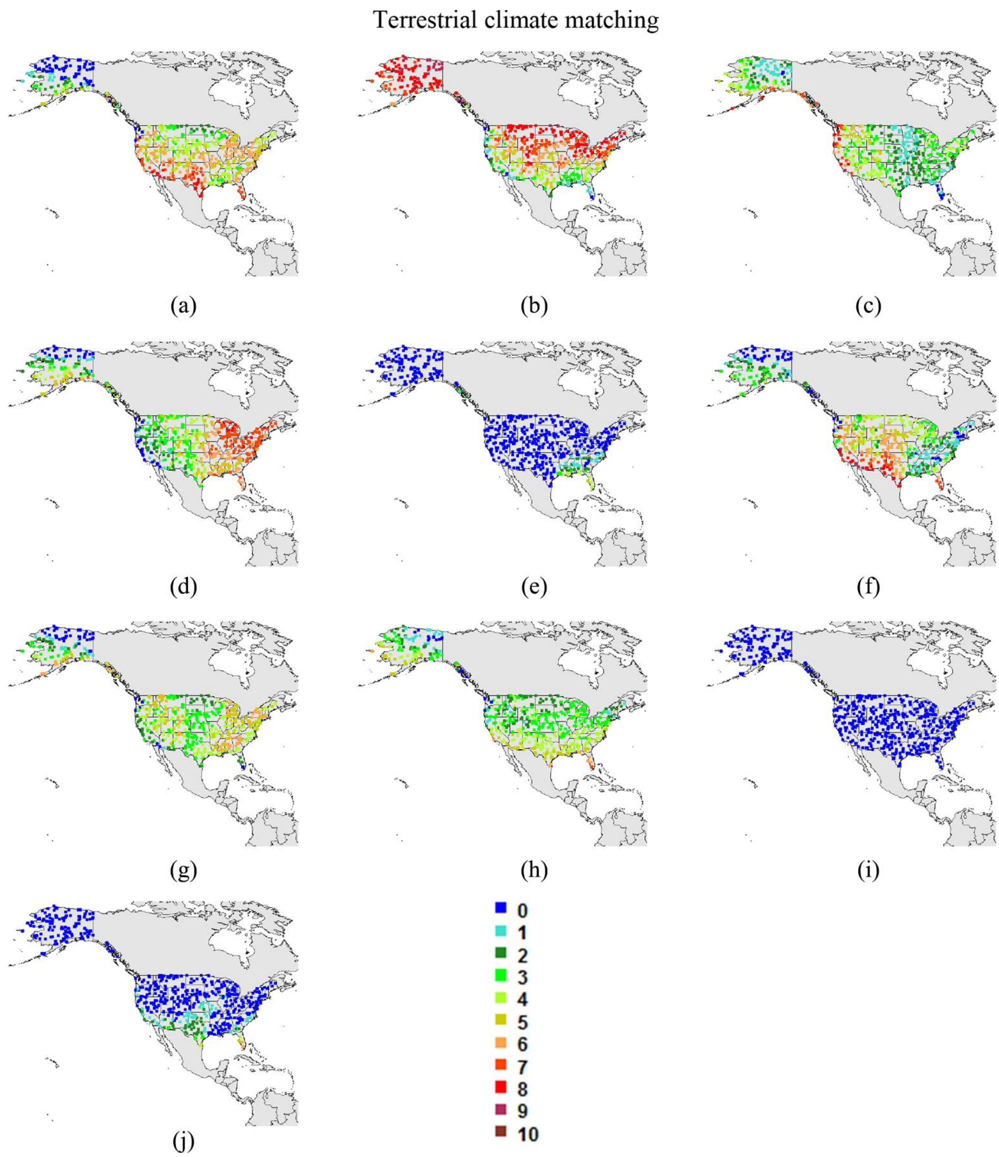

Figure 1. Terrestrial and marine climate matching. (a) Australia, (b) Canada, (c) Chile, (d) Japan, (e) Malaysia, (f) Mexico, (g) New Zealand, (h) Peru, (i) Singapore, and (j) Vietnam. *Note*: Colored observations on each map are meteorological stations. Euclidean distance is calculated for each station to determine a score for climate similarity with stations in the partner country. Stations with a score of 0 (blue) have no climate similarity. Scores of 10 (dark red) have the highest degree of climate similarity with stations in the partner country.

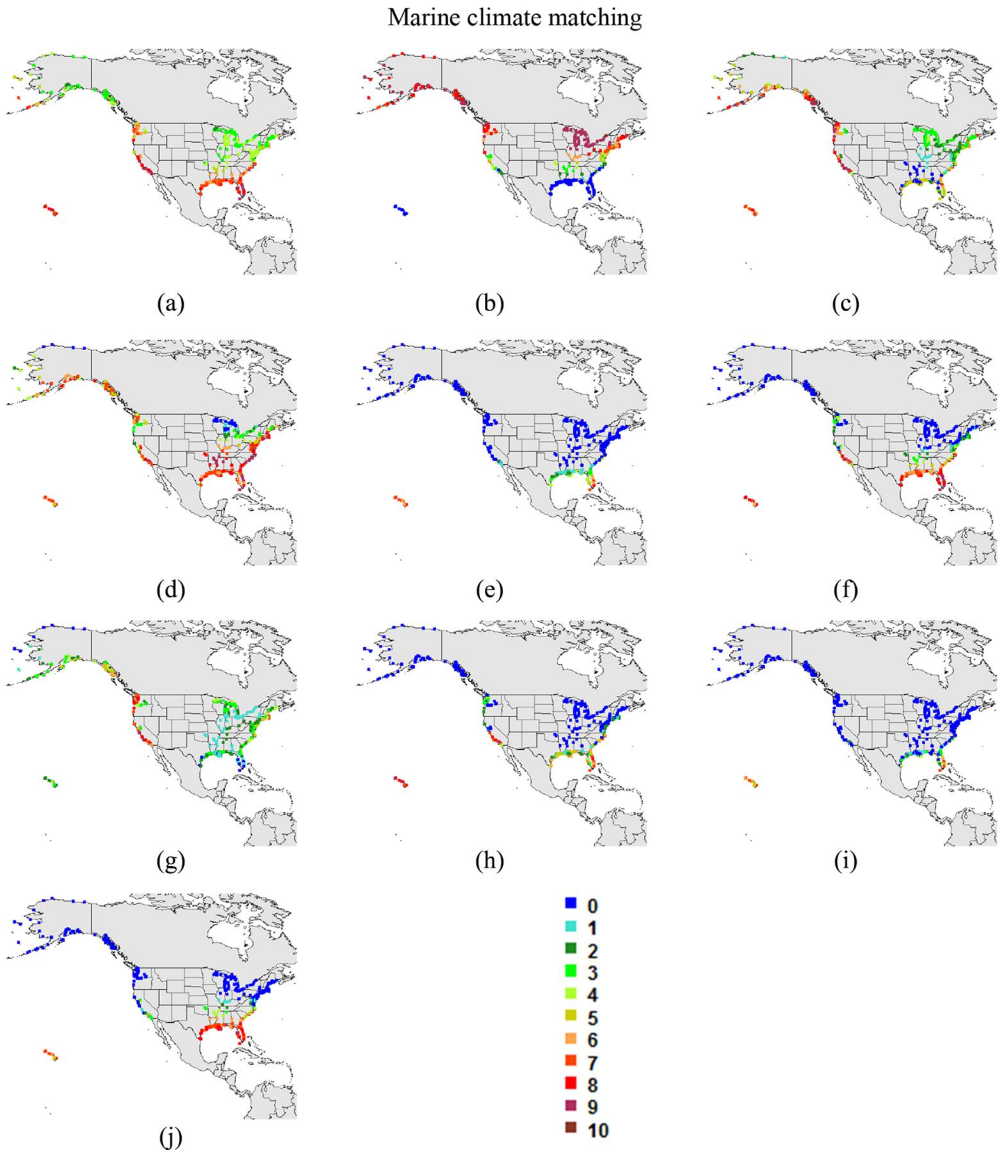

Figure 1. Continued.

$$d_j = \left[1 - \min_{i \in \text{sites}} \left(\sqrt{\frac{1}{k} \sum_k \frac{(y_{ik} - y_{jk})^2}{\sigma_k^2}} \right) \right] * 10 \tag{4}$$

where i and j are the stations in source and destination regions, respectively, and y_{ik} and y_{jk} are the k^{th} climate variable for the i^{th} and j^{th} stations, or port. For each U.S. meteorological station or port, the lowest Euclidean distance among all source stations or ports was then selected as the climate score for that U.S. station or port and was expressed in a scale from zero (lowest climate match) to 10 (highest climate match) (for more detail of this approach, see Elmore and Richman (2001)). Our final measure of climate similarity, C_j, is the percentage of meteorological stations or ports in the United States with a climate score of 7 or higher. This cutoff was selected because it is associated with moderate to high NIS risk in other analyses (Bomford et al. 2009) and because it resulted in a larger range of C_j among sources countries (0–0.54) allowing for better discrimination. Analyses using climate score cutoffs of 5, 6, 8, and 9 are provided in Supplemental Material.

Results

Risk of Introduction—Changes in Trade

Table 2 shows the percentage changes in imports by sector and source. Positive values represent net increases in U.S. imports, which serve as a proxy for potential changes in trade flows resulting from increased economic integration of the Asia-Pacific region. We focus on the percentage changes in trade flows for the risk of introduction employed to calculate the invasion risk index and provide the corresponding absolute changes in U.S. imports in Supplemental Materials Table A2. The United States currently has preferential trade agreements (PTA) with many countries in the region including Australia, Canada, Chile, Mexico, Peru, and Singapore. However, the remaining trade partners in the analysis, including Japan, Vietnam, Malaysia, and New Zealand, are not currently covered under a U.S. PTA (U.S. Trade Representative 2016) and are expected to be sources of the largest percentage changes in U.S. imports. Meat and processed food imports are expected to increase substantially from Australia and New Zealand. Peru is also likely to become a significant source of processed food. Imports increase substantially for meat and labor-intensive manufacturing from Vietnam. Changes in imports from Canada and Mexico are relatively modest, and imports overall are expected to decrease from Chile, Australia, and Singapore, as imports from non-PTA countries become relatively more competitive. Canada and Mexico have always been important trade partners for the United States, with extensive market access under the North American Free Trade Agreement (NAFTA), and further liberalization in the Asia-Pacific region is expected to have little effect on trade within North America overall. However, it is important to note that the current renegotiation of NAFTA may have trade implications for the region that are not considered in this analysis.

Table 2. Percentage changes in quantity of U.S. imports* in 2025 with Pacific Rim liberalization.

	Australia	Canada	Chile	Japan	Malaysia	Mexico	New Zealand	Peru	Singapore	Vietnam	Rest of world
Rice and sugar	−0.9	0.5	−0.4	6.2	7.3	0.1	5.4	−0.1	−0.2	3.7	0.0
Other crops	−2.8	0.2	−0.2	4.9	3.9	0.5	4.3	0.0	−5.0	−3.0	0.3
Fruits and vegetables	−1.9	0.1	−0.3	16.6	4.1	0.3	−0.4	0.1	−5.5	−2.0	0.2
Live animals	−1.5	0.2	−0.3	5.4	2.0	0.6	0.0	0.0	−1.6	1.4	0.2
Resources	−0.2	0.0	−0.1	−0.1	−0.1	0.1	−0.3	0.2	−0.2	−2.7	0.0
Meat	11.3	0.6	−2.6	27.3	11.2	−1.3	8.4	0.3	−0.7	67.0	−0.9
Processed food	9.8	2.4	0.0	7.8	1.4	−0.4	13.2	17.3	3.2	2.2	−0.4
Labor-intensive manufacturing	−0.1	−0.1	−0.2	1.6	1.0	−0.1	1.0	0.0	−0.4	18.2	−0.2
Capital-intensive manufacturing	−0.3	0.0	−0.1	2.9	5.0	0.0	1.8	0.1	−0.1	3.8	−0.1
Services	−0.3	0.0	−0.2	−0.7	−0.5	0.2	−2.1	0.3	−0.5	−3.5	0.0

*Weighted average.
Source: Burfisher et al. 2014 and authors' calculations.

Risk of Establishment—Climate Matching

Table 3 and Figure 1 show terrestrial and marine climate similarities between the United States and Pacific Rim trade partners. Canada, Japan, Mexico, and Australia have the greatest terrestrial climate similarity to the United States Canada matches well with most of the terrestrial climate of the United States, with the greatest similarity found in the colder northern half of the country. Japan matches most with the terrestrial climate of the eastern United States, while Australia matches particularly well with the Southwestern United States. Mexico matches well with the West Coast, the southwest, and with Florida, but matches poorly with the wetter portions of the north, Midwest, and east. Chile matches poorly with most of the U.S. terrestrial climate, except for the West Coast, while Malaysia does not match highly with the terrestrial climate in any part of the United States. New Zealand and Peru match poorly with most of the U.S. terrestrial climate, Singapore and Malaysia match poorly with the entire U.S. terrestrial climate, and Vietnam only matches with the southernmost tip of Florida.

In general, the risk of establishment in U.S. ports is highest for trade with Canada, Japan, Australia, and Vietnam, with nearly half of U.S. ports closely matching port climates in Canada and Japan, and 38% matching in Australia at an index greater than a value of 7. Many ports are highly susceptible to risk for establishment from a few partners that do not necessarily threaten the broader United States. Port climates in the southeastern United States closely match port climates in Central America and Southeast Asia. Malaysia, Mexico, Peru, Singapore, and Vietnam all closely match ports in the Gulf of Mexico, even though they pose relatively little threat to the colder waters of the Great Lakes and Northeast. If a trading partner poses a significant threat to the Great Lakes and Northeast, however, it likely poses a threat to the rest of the country, with the exception of Canada, which poses little threat to the warmer ports in the south.

Table 3. Similarity of terrestrial and marine environments.

	Number of grid cells with match equal to:													
Score	0	1	2	3	4	5	6	7	8	9	10	Total	$P > 7$ (%)	$P > 8$ (%)	$P > 9$ (%)
Terrestrial															
Australia	74	14	28	44	107	112	115	40	16	2	0	552	10.5	3.3	0.4
Canada	6	17	13	32	48	64	73	101	167	31	0	552	54.2	35.9	5.6
Chile	8	105	112	137	110	40	13	14	12	1	0	552	4.9	2.4	0.2
Japan	44	26	66	103	70	79	61	92	11	0	0	552	18.7	2.0	0.0
Malaysia	497	23	18	4	9	1	0	0	0	0	0	552	0.0	0.0	0.0
Mexico	58	72	75	72	81	72	64	29	20	9	0	552	10.5	5.3	1.6
New Zealand	47	20	64	129	125	123	44	0	0	0	0	552	0.0	0.0	0.0
Peru	17	36	96	194	139	60	8	2	0	0	0	552	0.4	0.0	0.0
Singapore	552	0	0	0	0	0	0	0	0	0	0	552	0.0	0.0	0.0
Vietnam	449	53	36	7	2	3	2	0	0	0	0	552	0.0	0.0	0.0
Marine															
Australia	0	0	8	135	114	33	51	128	55	28	0	552	38.2	15.0	5.1
Canada	177	3	9	30	22	19	38	43	76	133	2	552	46.0	38.2	24.5
Chile	77	22	90	105	26	91	38	46	28	29	0	552	18.7	10.3	5.3
Japan	30	13	28	46	42	42	99	122	90	40	0	552	45.7	23.6	7.2
Malaysia	370	63	56	14	21	4	7	9	8	0	0	552	3.1	1.4	0.0
Mexico	246	30	23	31	16	11	53	69	48	25	0	552	25.7	13.2	4.5
New Zealand	28	145	97	123	56	23	27	16	28	9	0	552	9.6	6.7	1.6
Peru	291	47	59	17	23	48	24	21	15	7	0	552	7.8	4.0	1.3
Singapore	445	37	19	17	9	6	3	16	0	0	0	552	2.9	0.0	0.0
Vietnam	316	19	10	14	10	7	17	73	81	5	0	552	28.8	15.6	0.9

Risk of Invasion

The invasion risk index values for each source country are included in Table 4. Risk of invasion is a function of risk of introduction and risk of establishment. The largest risk to terrestrial environments is associated with trade from Japan, particularly in the eastern United States. For example, Japanese meat presents the largest risk for NIS invasion, while Japanese fruits and vegetables, processed food, and rice are also large sources of risk. Increased Japanese meat trade could introduce novel pathogens, such as recently detected antibiotic resistant strains of *Escherichia coli* in Japanese cattle (Yamamoto et al. 2014), or NIS could be introduced through ballast water or hull fouling from the refrigerated container ships that typically transport meat. Species such as the vinegar fly *Drosophila suzukii* Matsumura (spotted wing drosophila) that hitchhike on Asian fruit imports threaten both stone and soft fruits in the United States. (Walsh et al. 2011). Similarly, the Citrus Longhorn Beetle (*Anoplophora chinensis*), which is currently found in Japan, Malaysia, and Vietnam, poses a threat through imports of ornamental plants (bonsais, etc.) that are expected to increase due to trade liberalization.

For all trade partners except Canada, marine environments are more at risk than terrestrial environments. Vietnam poses a high threat due to increases in meat trade transported by cargo ships and particularly good matches between Vietnamese ports and the majority of the southern U.S. coastline. We also see high risk for marine invasion from Japan in U.S. ports due to close matches and increased trade expected with liberalization. These changes will likely increase risk of an invasion by golden mussels (*Limnoperna fortunei*), freshwater mussels expected to be the next great invader in the United States. They pose a substantial threat to the Laurentian Great Lakes and other freshwater systems

Table 4. Terrestrial and marine invasion risk index.

	Rice and sugar	Other crops	Fruits and vegetables	Live animals	Resources	Meat	Processed food	Labor-intensive manufacturing	Capital-intensive manufacturing	Services
					Terrestrial					
Australia	−0.09	−0.29	−0.20	−0.16	−0.02	1.19	1.03	−0.01	−0.03	−0.03
Canada	0.27	0.11	0.05	0.11	0.00	0.33	1.30	−0.05	0.00	0.00
Chile	−0.02	−0.01	−0.01	−0.01	0.00	−0.13	0.00	−0.01	0.00	−0.01
Japan	1.16	0.91	3.10	1.01	−0.02	5.09	1.46	0.30	0.54	−0.13
Malaysia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.01	0.05	0.03	0.06	0.01	−0.14	−0.04	−0.01	0.00	0.02
New Zealand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Peru	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00
Singapore	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vietnam	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					Marine					
Australia	−0.34	−1.07	−0.73	−0.57	−0.08	4.32	3.75	−0.04	−0.11	−0.11
Canada	0.23	0.09	0.05	0.09	0.00	0.28	1.10	−0.05	0.00	0.00
Chile	−0.07	−0.04	−0.06	−0.06	−0.02	−0.49	0.00	−0.04	−0.02	−0.04
Japan	2.83	2.24	7.58	2.47	−0.05	12.46	3.56	0.73	1.32	−0.32
Malaysia	0.22	0.12	0.13	0.06	0.00	0.34	0.04	0.03	0.15	−0.02
Mexico	0.03	0.13	0.08	0.15	0.03	−0.33	−0.10	−0.03	0.00	0.05
New Zealand	0.52	0.41	−0.04	0.00	−0.03	0.81	1.27	0.10	0.17	−0.20
Peru	−0.01	0.00	0.01	0.00	0.02	0.02	1.35	0.00	0.01	0.02
Singapore	−0.01	−0.14	−0.16	−0.05	−0.01	−0.02	0.09	−0.01	0.00	−0.01
Vietnam	1.07	−0.86	−0.58	0.40	−0.78	19.30	0.63	5.24	1.09	−1.01

in the United States. Able to survive brief exposure to seawater, the golden mussel has spread from its native range in China to Taiwan, Argentina, and Japan through ships' ballast water and hull fouling, which is of particular concern given the close match for marine environments and expected increases in trade for a variety of product categories between the United States and Japan.

The United States has high climate matches with Canada, Mexico, and Australia. However, the expected changes in imports from these countries is relatively modest, given that there are already trade agreements in place allowing for substantial trade to occur, with the exception of increases in meat and processed food imports expected from Australia. Accordingly, new trade, and therefore new NIS risk, will likely have small effects on trade between these countries relative to other members where no other trade agreements are in effect. Further, in the case of Canada and Mexico, NIS may spread naturally, given that these countries are contiguous with the United States. A few countries, such as Malaysia, are likely to see significant increases in trade but have few places that match either the terrestrial or marine environments of the United States except for southern Florida and the Gulf of Mexico.

To provide additional information regarding potential invasion risk, we provide Supplemental Material that includes risk invasion indices that account for varying degrees of environmental similarity of marine and terrestrial environments (Supplemental Material Tables A3–A6). Burfisher et al. (2014) conducted sensitivity analysis to test the robustness of results, which are described in the Supplemental Material. Results from varying import demand elasticities (key parameters assumed in the model) show that changes in U.S. imports from each supplier are less than a +/− 1 percentage point deviation, in general, in the expected change in total U.S. imports from each supplier with 95% confidence. Given the robustness of results, in tandem with the general consensus in the international trade literature regarding key changes in expected trade flows resulting from increased trade liberalization in the Pacific Rim, we hold changes in trade flows constant and vary the threshold for environmental similarity. The key results from our sensitivity analysis reveal increased threat for NIS spread from all trade partners when a lower level of environmental similarity is employed for terrestrial and marine environments. Higher thresholds for environmental similarity emphasize the most vulnerable sources of tradable products, highlighting the potential NIS threat resulting from increased trade with Japan.

Conclusion

The United States continues to explore further economic integration with countries in the Asia-Pacific region despite the failure of the Trans-Pacific Partnership. Moving forward, there is an opportunity for further attention to be given to the risk of NIS spread if trade patterns are altered. The economic impacts of NIS have been well documented (Perrings, Dalmazzone, and Williamson 2000; Perrings et al. 2002; Horan et al. 2002; Perrings et al. 2005; Lovell, Stone, and Fernandez 2006; Olson 2006; Meyerson and Mooney 2007; Hulme 2009; Warziniack et al. 2018), as have the environmental impacts of trade agreements (Grossman and Krueger 1994; Copeland and Taylor 1995; Antweiler, Copeland, and Taylor 2001). However, this is the first study to explore the changes for both terrestrial and marine NIS risk resulting from increased economic integration of the Asia-Pacific region.

This work provides the basis of a risk assessment prediction system to examine the effect of changes in trade patterns on the risk for NIS spread, which merits increased attention in the policy arena as future trade agreements are considered. Understanding the key sources of risk, including trade partners and sectors, further informs what should be prioritized by future NIS mitigation strategies to accompany increased economic activity between the United States and key trade partners. This research also highlights the importance of maintaining current NIS risk mitigation strategies for trade of certain commodities and between certain trade partners. Risk of introduction is determined by changes in trade flows, while terrestrial and marine climate similarities between countries determine the risk of establishment. Risk of introduction and establishment combine to create an overall measure of invasion risk. By employing results from a global economic modeling framework in tandem with data for environmental similarities between trade partners, we examine risk in a way previous attempts using only trade data (e.g., Keller et al. 2011, Xu et al. 2014) or only climate matching (e.g., Bomford et al. 2009, Britton et al. 2010, Kopecký et al. 2013, Howeth et al. 2016) cannot. While an important first step is to provide an NIS risk assessment defined by product category and trade partner for both marine and terrestrial environments, next steps include trade modeling efforts that allow the U.S. national trade estimates and flows to be disaggregated by U.S. region to better highlight coastal and terrestrial areas exposed to the greatest risk for NIS invasion. Furthermore, we aim to link specific pest and pathogen profiles to each product category and trade partner to inform the potential for invaders as well as damage estimates if an invasion of probable NIS were to occur.

Japan is the largest source of risk for NIS invasion to the United States, given the large changes in U.S. imports from Japan and high terrestrial and marine climate matching. Risks for establishment in U.S. terrestrial environments are also high from Canada, Mexico, Australia, and Chile, and risks for establishment in marine environments are high from Canada, Australia, Mexico, and Vietnam. However, given historical trade agreements with Canada and Mexico and borders that are contiguous with the United States, we anticipate relatively few new invaders to the United States from these countries.

This work, in its current form, has important policy implications. The United States continues to highlight that trade expansion between the United States and partners in Asia is likely to occur, either through a single multilateral agreement or through multiple bilateral agreements. Most notably, the United States has stressed the importance of seeking a trade agreement with Japan, which poses considerable risk for NIS spread, especially if NIS mitigation strategies are not employed. This research considers full trade liberalization of the Asia-Pacific region, which may overestimate future trade effects if market access reform is more modest in scope. Furthermore, the United States is in the process of beginning a renegotiation of NAFTA, and this work provides important information on NIS risk between the United States and NAFTA partners.

Further information regarding NIS risk, and risk assessment prediction systems, are needed to limit the future invasion of NIS resulting from changing trade patterns. The best risk assessments will be specific to both the country of species origin and the type of trade good likely to harbor the species. Policy measures will be most effective by focusing on specific types of cargo from the most risky partners. Maps indicating environmental similarity of both marine and terrestrial environments, as presented in this research, can enhance risk assessments by showing which parts of the United States are most likely to be threatened by NIS from partner countries. Sector-specific economic analysis that is linked to pest and pathogen profiles can go a step further to provide even greater detail on sources of NIS risk. Efforts are underway to collect the data needed for expanded NIS risk assessments, and continued research will provide more detailed assessments for potential U.S. hot spots and risky partners concerning nonindigenous species risk related to expanded trade in the Asia-Pacific region. In an era of increasing demand for data and research findings to fuel negotiations for trade agreements, this work fills an important gap by proving an assessment of the expected changes in nonindigenous species risk, given increased economic integration in the Asia-Pacific region.

Note

1. Original TPP countries included Australia, Brunei, Canada, Chile, Japan, Malaysia, Mexico, New Zealand, Peru, Singapore, Vietnam, and the United States.

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