Economic Determinants of Invasion and Discovery of Nonindigenous Insects

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Introductions of nonindigenous organisms into the United States have been linked to international trade. The individual contributions of imports, immigration, and international travel, however, are poorly understood because introduction dates are unavailable. We examine relationships between economic trends and discoveries of nonindegenous insects and use these relationships to infer the timing and determinants of introductions. We find that a few variables can explain much variation in species introductions and identifications. The most significant contributor to the introduction appears to be agricultural imports. Currently available proxies for academic effort are weak determinants of the probability that introduced species are identified.

Key Words: identifications, insects, introductions, invasive species, nonindegenous

JEL Classifications: F18, N7, Q56

The majority of introductions of nonindegenous organisms into the United States are believed to have been facilitated by human beings (National Research Council).[1] The cumulative number of identified insect species has increased steadily since 1820, a pattern that has been attributed to growth in international trade (Dehnen-Schmutz et al.; Elton; Frey; Levine and D'Antonio; Maki and Galatowitsch; Niemela and Mattson; Perrings et al.; Sailer 1978, 1983; Stanaway et al.; Weigle et al.) and travel (Johnson, Ricciardi, and Carlton; Liebhold et al.; Office of Technology Assessment) and natural habitat destruction (Pimentel, 1993; Taylor and Irwin; Vilà and Pujadas). Early introductions have been associated with European migration (Smith; Wheeler and Hoebeke), the surge in animal and plant imports following the founding of the U.S. Department of Agriculture (USDA) (Sailer, 1983), and large-scale commercial production of homogeneous crops and livestock (Capinera). Advances in transportation, storage, and shipping technologies (Dobbs and Brodel; Dowell and Gill; Myers;

[1] In 1983 1,683 species were counted in the United States, which was 298 more than in 1978 and over 1,220 more than in 1860 (Sailer 1978, 1983). As of today, 4,600 nonindegenous insect species are established in the United States, including Hawaii and other territories. In 1940, damages were $1.6 billion, excluding expenditures on prevention, and $3 billion, including prevention costs (Sasscer). Nonindegenous insect pests destroy approximately 9%, or $19 billion, of U.S. crops annually (Pimentel et al., 2000, 2001).

The total damages by all insect species are estimated at $40 billion (Pimentel, Zuniga, and Morrison). Since different types of costs are included in different studies, these damage estimates are not directly comparable. The true damages—including all expenditures on prevention and mitigation—are likely to be even greater.

Pratt et al.; Rainwater) have also been implicated, as has the dumping of overseas soil ballast (Lindroth; Locke et al.; Pierce et al.) and the widespread use of wood packaging materials (Haack and Cavey).

Although there is a great deal of circumstantial evidence suggesting a causal relationship between the previously mentioned factors and introductions of nonindegenous organisms, there are few studies that have estimated such relationships empirically. Work et al. use Agricultural Quarantine Inspection Monitoring data to examine the contributions of four distinct cargo pathways. Taylor and Irwin use a nationwide database of exotic plants to examine the effects of population and land use variables on the dispersion of plants. Similarly, Dalmazzone and Vilà and Pujadas use regression analysis to study the relationship between macroeconomic factors (national wealth, trade flow, tourism, immigration, population density, and land use) and the concentration of nonindegenous plants in various countries. The three latter studies find that economic variables contribute significantly to the prevalence of nonindegenous plants.

However, the existing studies are limited to short time series of data and to methods that implicitly equate species identifications to species introductions. In effect, all introduced species are assumed to be known, and the identifications occur at the time of arrival; therefore, it is unclear how general and robust the findings are. Additionally, the majority of the existing studies focus on the dispersion of plants, so it is unclear whether the findings are relevant to insect species. As a result, there is very little in the way of available scientific guidance to characterize the historic importance of various pathways to insect invasion. Our objective is to examine the influence of pathways on observed identifications of nonindegenous insects and unobserved introductions using data for a large number of years. We find that agricultural imports and the volume of sea trade may explain a great amount of variation in insect identification and introduction rates; however, the impacts of immigration and travel are unclear, and currently available proxies for identification effort are weak determinants of the probability that new species are identified after they are introduced.

The Model

The objectives of the analysis are to measure the impacts of international trade and travel on the number of nonindegenous insect species introduced into the United States and the success of academic and governmental efforts to identify introduced species. The model, therefore, has two parts that are estimated jointly: the process of species introductions and the likelihood of identifying introduced species. This model makes it possible to infer the introduction rate of nonindegenous species using the record of actual identifications, even if the events of introduction and identification are separated by years. In effect, this model eschews the bias from assuming simultaneous introductions and identifications.

Following Costello and Solow, the processes of introduction and identification of invasive species are modeled as Poisson random variables, the distributions of which include economic factors. μ_s denotes the number of introductions in year s and is modeled as an exponential function of trade–related factors:

$$(1) \quad \mu_s = \exp(\beta \cdot X_s).$$

X_s is a vector of explanatory variables, and β is a vector of parameters. μ_s is assumed to depend only on economic factors in year s. Let π_{st} denote the probability that a species is observed in year t given that it was introduced in year s, $s \leq t$, modeled as a logistic function of the amount of identification effort and resources,

$$(2) \quad \pi_{st} = \frac{\exp(\gamma \cdot W_{st})}{1 + \exp(\gamma \cdot W_{st})}.$$

W_{st} is a vector of explanatory variables, and γ is a vector of parameters. W_{st} may be specific to an identification in year t or to a pair of introduction and identification years s and t, so in general it has two time subscripts. The probability that a species is observed in a year is assumed independent but not necessarily the same across different years.

In period t, the probability of identifying a species that was introduced in period s (p_{st}) equals the product of the probability of observing the species in period t and the probability of not observing the species in all periods s through $(t-1)$:

$$(3) \quad p_{st} = \pi_{st} \prod_{j=s}^{t-1} (1 - \pi_{sj}).$$

The number of species introductions (μ_s) may depend on the volume of imported goods (goods arrival), the number of arriving people (passenger arrival), and the migration of species unrelated to trade (wildlife migration), as in

$$
\begin{aligned}
\mu_s = \ & \exp(\beta_0 + \beta_1 \cdot \textit{goods arrival}_s \\
& + \beta_2 \cdot \textit{passenger arrival}_s \\
& + \beta_3 \cdot \textit{wildlife migration}_s).
\end{aligned}
$$
(4)

Unfortunately, there is no single index for all goods arriving into the United States. Different goods are susceptible to infestation to a different degree because of their type (produce versus durables), origin (forest versus factory), or packaging (wood versus metal containers). Passenger arrivals also vary in their propensity for introducing insect species because different types of passengers bring different types of luggage (visitors versus immigrants), on different means of conveyance (air versus water), and from different climates (tropics versus arctics). Trade data disaggregated by these pathways are often missing. But even if they were available, it would be difficult to use them because the number of records that we are examining, the annual counts of species identifications, is small. It is also expected that individual trade series are collinear with each other. Including them all would lead to problems with the identification of individual parameters and yield parameters of unstable magnitudes and signs.

All the previously mentioned variables are individually expected to contribute positively to species introductions. However, if two factors are collinear with each other and an increase in one occurs with a decrease in another (such as arrivals by air replacing arrivals by sea), their parameters may have unexpected signs. If a pathway that is strongly associated with insect introductions is replaced by another pathway that is only weakly associated, the parameter on the second pathway could be negative even if we exclude the first factor from the regression.

The probability of identification of a species during years s to t depends on identification effort and resources and the observability of the species:

$$
\begin{aligned}
\pi_{st} = \ & \exp(\gamma_0 + \gamma_1 \cdot \textit{effort}_t \\
& + \gamma_2 \cdot \textit{resources}_t \\
& + \gamma_3 \cdot \textit{observability}_t) \\
& \div [1 + \exp(\gamma_0 + \gamma_1 \cdot \textit{effort}_t \\
& + \gamma_2 \cdot \textit{resources}_t \\
& + \gamma_3 \cdot \textit{observability}_t)].
\end{aligned}
$$
(5)

Unfortunately, consistent measures of academic, governmental, and private efforts to identify new species are unavailable. There is substantial overlap between the effort to identify new species and those to mitigate or control already identified pests. Local, regional, and national identification efforts have different goals. Efforts exerted by different agencies are, furthermore, likely to be highly correlated. Finally, effort, as the intensity of intellectual and manual labor, is difficult to measure. These shortcomings also exist for proxies for the available identification resources. Even with information on man-hours or spending, it is unclear how efficiently those resources are used. Various agencies, public institutes, and private entities report their statistics inconsistently and with insufficient detail. Their funding decisions may, furthermore, be highly correlated.

Observability of a species changes as it migrates to a more populated area, disperses to a wider area, attacks commercial crops, mutates, or becomes extinct. Because there are no data to characterize such trends, we assume that time t and the length of the period separating introduction and the current period $t–s$ are sufficient proxies for these trends (Costello and Solow). As a result, exponential survival and dispersion rates are assumed identical for all identified insect species. Species identifications may also occur as a by-product

of unrelated scientific or economic activities that are not monitored or measured (Myers). Species identified in these ways are not explicitly estimated in our model and therefore become part of the estimation residual.

In general, the lag between species introduction and identification ($t–s$) can be of any length. Unfortunately, for estimation purposes, we cannot allow unlimited lags between species introductions and identifications because we would need to observe all past values of variables explaining those identifications. With a limited time lag ($t–s$), we need data only on years s through t. In the current analysis it is assumed that the events of introduction and identification are separated by at most 10 years. This restriction allows us to use all of our annual observations of species identifications, without removing more than 10 years of data. In all model runs in the following, the initial year refers to the period when we start fitting species identifications. Therefore, assuming a maximum 10-year lag between species introduction and identification, the explanatory variables date back 10 years.

To estimate the parameters in Equations (1) to (3) (or specifically in Equations (3) to (5)), a maximum likelihood procedure is used to fit the estimated number of annual identifications to the actual identification record. The Poisson log-likelihood function over parameters in μ_s and π_{st} is

$$(6) \quad \log L = \sum_t [y_t \log(E(y_t)) - E(y_t)],$$

where y_t denotes the number of identifications in year t and the expected number of identifications, using the Poisson distribution of y_t, is

$$(7) \quad E(y_t) = \sum_{s=1}^{t} \left[\mu_s \pi_{st} \prod_{j=s}^{t-1} (1 - \pi_{sj}) \right].$$

Data

Information on initial identifications of nonindegenous insect species represents the core of our data. The North American Nonindegenous Arthropod Database (NANIAD) in-

cludes 2,419 species.[2] For 1,233 species, the database lists some information on identification dates, either exact years or year ranges. Mattson et al. with a database updated in 2003, Beardsley (1962, 1979), Capinera, Frank and Thomas, Sailer (1978, 1983), and Thomas provide further information on species and identification dates used to obtain more exact dates and to verify records.[3] Data from these sources are merged. For example, when identification dates differ across databases, the earliest date is used, and observations with reliable and exact identification dates are used. Ten species identified during 1550–1820 are omitted because data on explanatory variables are unavailable. For the same reason, two species identified during 2001–2002 are omitted, for a final data set having 1,097 identifications during 1820–2000.

Explanatory variables are often unavailable for the entire time span of the identification record, particularly data on detailed subcategories of trade. For variables that are unavailable or not easily measurable, close proxies are used. Table 1 lists the available dependent and explanatory variables with their sources and parameters to be estimated. To control for the arrival of infested goods into the United States, we use agricultural imports and the volume of sea trade as alternative proxies. We expect agricultural imports to be an important determinant of insect introductions because of their close association with crops and livestock, historical detections at U.S. ports (Haack and Cavey),

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[2] For a description of the NANIAD, refer to Kim and Wheeler and Knutson et al. The NANIAD has the same origins as the North America and Western Hemisphere Invasive Arthropod Databases (NAIAD and WHIAD). The differences come from nonsystematic updating of the databases and changes in nomenclature over time.

[3] The problem with many surveys of nonindegenous insects is that their nomenclature is different from those in prior studies. It is often unclear whether the reported identification in a region is the same as identification in the United States overall. Additional sources that are not incorporated in our data include the Bishop Museum's Hawaiian Arthropod Checklist Database and data compiled by Dowell and Gill for California, Frank and McCoy for Florida, and Nishida and Beardsley for the Midway Atolls.

Table 1. Endogenous and Explanatory Variables, Data Sources, and Estimable Parameters

Variable	Description (Units)	Years Available
Endogenous variables		
μs	Introductions in year s (species)	1780–1993
$\pi_{s,t}$	Probability of observing species in t, given its arrival in s	1790–2003
$p_{s,t}$	Probability of identifying species in t, given its arrival in s	1790–2003
y_t, $E(y_t)$	Actual and estimated species identifications in year t	1790–2003
Explanatory variables		
t	Year of identification (100 years)	1790–2003
$t–s$	Years between arrival and identification (100 years)	1790–2003
$agric\ imp_s$	Agricultural imports ($trillion/year)[a]	1851–2003
$imports_s$	All imports ($1,000/year)[b]	1870–2003
$all\ arriv_s$	All passenger arrivals (billion persons/year)[c]	1870–2003
$immigr_s$	Immigration (million persons/year)[d]	1820–2003
$air\ arriv_s$	Passenger arrivals by air (billion persons/year)[e]	1931–2003
$sea\ trade_s$	Volume of merchandise trade by sea (kilotons/year)[f]	1947–1996
$ARS\ outlay_t$	Agricultural Research Service outlays ($billion/year)[g]	1953–2003
Parameters to be estimated		
β	Parameters on X_s in the species-introduction equation (Equation [4])	
γ	Parameters on W_{st} in the species-observation equation (Equation [5])	

Note: All monetary variables are deflated to 2003 dollars using Sahr.

[a] U.S. Census Bureau, Statistical Abstracts (1851–1908); U.S. Department of Agriculture, Economic Research Service, FATUS CY1970 Supplemental Table 2 (1935–1967); CY1981 Supplemental Table 1 (1968–1975); DARRS FATUS (1976–1988); and ARTS, FATUS, and HS (1989–2003), interpolated using constant growth rate (1909–1934).

[b] Estevadeordal, Frantz, and Taylor (1870–1890) and International Trade Commission (1891–2003).

[c] U.S. Department of Justice, Immigration and Naturalization Service, International Oversees Travel Monthly Review and Special Tabulations (1870–1893, 1931–1965); U.S. Census Bureau, Statistical Abstracts (1870–1893); and Bureau of Transportation Statistics and International Trade Administration, Office of Travel and Tourism Industries (1984–2003), includes all passenger arrivals by sea and air, interpolated using constant growth rate (1894–1930, 1966–1983).

[d] U.S. Census Bureau, Citizenship and Immigration Services

[e] U.S. Department of Justice, Immigration and Naturalization Service, International Oversees Travel Monthly Review and Special Tabulations (1931–1965), and Bureau of Transportation Statistics and International Trade Administration, Office of Travel and Tourism Industries (1984–2003), interpolated using constant growth rate (1966–1983).

[f] U.S. Department of Commerce, Annual Report of the Maritime Administration.

[g] USDA Budget Estimates, interpolated using constant growth rate (1983).

and widespread references in the literature. Imports by sea are also thought to contribute to insect introductions because a large portion of horticultural commodities and raw materials are imported by sea and because environmental conditions associated with dock and cargo areas often promote insect survival.

To examine the effects of international travel, we use data on all passenger arrivals, passenger arrivals by air, and immigration.[4]

[4] The majority of aviation-related data are collected by the International Air Transport Association, which does not make pre-1980 data available to the public. Available aviation data series include major airlines' passenger-miles (for years 1960–1992) and airborne

Without information on luggage and circumstances, it is difficult to rank these pathways *a priori*. Passenger arrivals by air may be less important at explaining species introductions

freight ton-miles (1971–1982) from Standard & Poor's Aerospace and Air Transport Industry Surveys. These data do not distinguish international and domestic travel. The distance of travel may have an opposite impact on introductions relative to flight volume because fewer organisms survive long travel. Data on the number of aircraft often include only major carriers or omit the size of aircraft, hence potentially biasing our results. Our data on passenger arrivals by air are unique because they include arrivals by both U.S. and foreign nationals and count each passenger once regardless of the number of flight legs, the size and utilization of the aircraft, or the identity of the carrier.

because of airport and aircraft storage area conditions. To the extent that arrivals by air may have over time replaced arrivals by other means, coefficient estimates may not represent *ceteris paribus* impacts on species introductions.

To explain the species identification trend, we use one proxy for the level of public effort and resources available for the identification of new insect species: annual outlays of USDA's Agricultural Research Service (ARS), which has historically conducted invasive species research and management. Unfortunately, sufficient data on more detailed federal budget items are unavailable or have not been reported consistently over time.[5] Information on other public, academic, and private efforts are generally unavailable. To the extent that ARS funds are at least in part used for new species identifications, we expect a positive impact of funds on identifications. Generally, the species identification Equation (5) could include even lags of this variable, but without information on the timing of the use of the funds, it is unclear what lags should be included. Because of the limited availability of these data, the inclusion of lags would shorten the time period over which the model can be estimated. It is therefore assumed that federal funds affect species identifications only in the period when they are spent.

The variables and data series described previously are often unavailable in complete form. Some span fewer years than from the first year of the invasive species record to the present time. In that case the model is run on a shorter range of years. Some variables have missing values surrounded by known values. In a few cases, competing data series are available, and it is unclear which series should be used.[6] To generate a complete data set, we use the following procedures. When data series have missing values, we interpolate the numbers using surrounding values and a constant annual growth rate. In the absence of better information, the interpolated numbers can be viewed as the expected values given the known values in surrounding years. When multiple data series are available for the same or different time periods, the series that is most compatible with other time periods is used.

To piece together data on all passenger arrivals into the United States, we use data on all arrivals for 1870–1893 (Statistical Abstracts), the sum of arrivals by sea and by air for 1931–1965 (Immigration and Naturalization Service), and arrivals by air for 1984–2003 (Bureau of Transportation Statistics and International Trade Administration). Data on passenger arrivals after 1931 include only passenger arrivals by air and sea, notably excluding terrestrial arrivals. Putting these data series together is justified on the grounds that travel by ship made up the vast majority of international travel prior to the 1930s, and air travel replaced it and virtually eliminated it by the 1950s. U.S. import series are compiled from International Trade Commission data for 1891–2003 and from data used by Estevadeordal, Frantz, and Taylor for 1870–1890. Models reported in the following section use combinations of variables that do not suffer from multicollinearity, based on correlation matrices and variance inflation factors, with the exception of one case (model 3), where high correlation coefficients and high

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[5] Other proxies that were collected are the annual appropriations and outlays of the U.S. Department of Agriculture (USDA) (for years 1839–2003) and the USDA's Animal and Plant Health Inspection Service (APHIS) (1972–2003) and the Bureau of Entomology and Plant Quarantine (BEPQ) (1932–1956). A search was also run on the Agricola server of the National Agricultural Library (NAL) for publications that dealt with invasive insect species and were registered with the NAL (1960–2003). The search included phrases with adjectives—"alien," "exotic," "nonnative," "nonnative," "nonindigenous," "nonindigenous," "invasive," "emigrant," "immigrant," and "adventive"—combined with nouns—"species," "insects," "arthropods," "plants," "organisms," and "pests" (Reichard and White). USDA, APHIS, and BEPQ outlays and the NAL publications were not helpful in explaining the species identification trend, likely because these outlays and publications had functions other than invasive species identification. Outlays by USDA and APHIS were estimated to have a small, negative effect on species identifications. The number of NAL publications had a negligible, positive effect.

[6] For instance, U.S. passenger arrivals are tallied with a different measure of precision by the Bureau of Transportation Statistics and the International Trade Administration and were historically measured by the U.S. Census Bureau.

Table 2. Estimation Results

	Model				
	1	2	3	4	5
Introduction rate constant (β_0)	1.011*	0.997*	−1.562**	−2.737*	0.733*
	(109.482)	(100.692)	(19.612)	(65.868)	(161.590)
Introduction rate t (β_1)	1.330*				
	(20.159)				
agric imp$_t$ (β_1)		52.584*	109.723*	165.233*	64.515*
		(228.806)	(60.058)	(175.610)	(135.944)
all arriv$_t$ (β_2)					−14.202
					(5.594)
immigr$_t$ (β_2)		−0.102	0.372	1.219	
		(0.594)	(0.488)	(6.360)	
air arriv$_t$ (β_3)			−74.571*	−61.492*	
			(45.094)	(36.280)	
air mail$_t$ (β_3)					
sea trade$_t$ (β_4)			2.085**		
			(18.242)		
Identification rate constant (γ_0)	−0.906	−524.198*	−446.753*	−394.797*	−628.398*
	(0.002)	(63.808)	(243.220)	(77.050)	(101.286)
Identification rate t (γ_1)	39.423*	30.410*	109.957*		42.522*
	(19.847)	(37.448)	(85.562)		(62.908)
ARS outlay$_t$ (γ_1)				−3.829	
				(0.500)	
Identification rate	−3.373	473.894*	407.059*	385.331*	567.973*
(t–s) (γ_2)	(0.036)	(63.004)	(243.336)	(73.916)	(101.562)
Log likelihood	1,241.42	1,278.29	869.35	763.73	1,263.63
Log-likelihood ratio	380.45*	304.06*	525.48*	256.95*	290.25*
Degrees of freedom	3	4	6	5	4
Years	1866–1990	1866–1990	1958–1996	1964–1998	1882–1990

Note: χ^2 statistics are in parentheses. The dependent variables are the annual number of species introductions (for regressors with coefficients β_x) and the likelihood of observing a species t–s years after introduction (for regressors with coefficients γ_x). All monetary variables are deflated to 2003 dollars using Sahr.
* Coefficient is significant at the 0.1% level.
** Coefficient is significant at the 1% level.

variance inflation factors among two variables are noted.

Results

The Naive Model

We start with "naive," noneconomic model 1 proposed by Costello and Solow where introduction and observation rates (Equations [4] and [5]) are only functions of time and a time lag between introductions and identifications for 1866–1990. We discard earlier observations because the recording of identifications of new species was intrinsically

different before 1866 and discard more recent observations because some new identifications may not have shown up in our data.

$$(8) \quad \mu_t = \exp(\beta_0 + \beta_1 \cdot t)$$

$$(9) \quad \pi_{st} = \frac{\exp(\gamma_0 + \gamma_1 \cdot t + \gamma_2 \cdot \exp(t - s))}{1 + \exp(\gamma_0 + \gamma_1 \cdot t + \gamma_2 \cdot \exp(t - s))}$$

Coefficient estimates on the time variables are significantly different from zero and imply that rates of species introduction and identification have grown over time (Table 2). The log-likelihood ratio for model 1, compared to a model with all coefficients except the intercept restricted to zero, is 380.45; therefore, the

hypothesis that our regressors jointly explain none of the variation in annual species identifications can be rejected at the 0.1% level.

The Live-Organism Pathway Model

In model 2, we replace time t as a regressor in the expression for μ_t (Equation [8]) with the volume of agricultural imports and immigration; therefore, this model implicitly assumes that trade and travel are the most important determinants of live organism introductions:

$$(10) \quad \mu_t = \exp(\beta_0 + \beta_1 \cdot agric\ imp_t + \beta_2 \cdot immigr_t).$$

The process of species identification is assumed to follow Equation (9). Model 2 is examined for 1866–1990, allowing a direct comparison of fit to model 1. The coefficient on agricultural imports is positive, as expected, and significant at the 0.1% level, while the coefficient on immigration is negative and insignificant. γ_2 characterizes the effect of the length of time between species introduction and identification and is positive and significant at the 0.1% level. In all the models that follow, γ_2 is positive implying that, in all but the naive model, species are generally observed in later years, after their arrival, presumably because of their dispersion. The log-likelihood function value is higher for model 2, indicating an improvement in fit relative to model 1, and the log-likelihood ratio statistics indicates that the hypothesis that our regressors jointly explain none of the variation in species identifications can be rejected at the 0.1% level.

The Air And Sea Pathway Model

In model 3 we add airline passenger arrivals and sea trade tonnage to the list of explanatory variables examined because both pathways have been described as important. In particular, air travel may allow insects to survive longer journeys:

$$
(11) \quad
\begin{aligned}
\mu_t = \exp(&\beta_0 + \beta_1 \cdot agric\ imp_t \\
&+ \beta_2 \cdot immigr_t + \beta_3 \cdot air\ arriv_t \\
&+ \beta_4 \cdot sea\ trade_t).
\end{aligned}
$$

The process of identification is assumed to follow Equation (9). The model is run for 1958–1996 at the expense of almost a century's worth of identification data because the volume of sea trade is unavailable before 1947. Years 1991–1996 are added to compensate for this loss, at a risk of using incomplete data on species identifications for those years. Model 3 excludes World War II; therefore, the period examined may be less subject to a structural change than the previous periods examined.

Air arrivals are used instead of all arrivals because they have made up the vast majority of all U.S. arrivals since the early 1950s. Conceptually, because all arrivals comprise passengers arriving by air and sea, they could be collinear with sea trade. Including both variables could cause problems in identifying parameters on these two factors. To test for collinearity between all arrivals and sea trade, the variance inflation factor was computed, and a factor of 8.4 was obtained. Given that variance inflation factors over 8.0 are taken to indicate collinearity, all arrivals should not be used jointly with sea trade in a regression. The variance inflation factor between sea trade and air arrivals is 7.9, indicating a potential problem but not a prohibiting result. Passenger arrivals, or arrivals by air, could also be collinear with immigration. The variance inflation factor between either measure of passenger arrivals and immigration is, however, only 3.7.

Coefficient estimates on all variables except immigration are highly statistically significant. Agricultural imports, immigration, and the volume of sea trade have the expected positive effect on species introductions. Air arrivals have an unexpected large negative effect, possibly because of their partial collinearity with sea trade, omitted variables, or perhaps measurement errors (Vining). The coefficient estimates and their significance suggest the joint importance of the included factors in explaining species introductions and identifications, but the small time dimension introduces the possibility of overidentification. Model 3 uses eight explanatory variables to explain 38 identification records; nevertheless, the hypothesis that our regressors jointly explain none of the variation in species

identifications is again rejected at the 0.1% level.

The Species Identification Effort Model

Model 4 uses data on ARS outlays to proxy for federal efforts to identify new species Equation (5). Because of the short data series available on ARS outlays, this model is limited to the years 1964–1998. The species introduction Equation (4) is assumed to depend on the volume of agricultural imports, immigration, and passenger arrivals by air:

$$(12) \quad \begin{aligned} \mu_t = {} & \exp(\beta_0 + \beta_1 \cdot agric\ imp_t \\ & + \beta_2 \cdot immigr_t + \beta_3 \cdot air\ arriv_t) \end{aligned}$$

$$(13) \quad \begin{aligned} \pi_{st} = {} & \exp(\gamma_0 + \gamma_1 \cdot ARS\ outlay_t \\ & + \gamma_2 \cdot \exp(t-s)) \\ & \div [1 + \exp(\gamma_0 + \gamma_1 \cdot ARS\ outlay_t \\ & + \gamma_2 \cdot \exp(t-s))] \end{aligned}$$

Compared to model 3, sea trade is excluded here as a factor to preserve degrees of freedom; it is assumed that agricultural imports proxy well for the arrival of high-risk commodities.

The coefficient on ARS_t is negative, small in magnitude, and insignificant, suggesting that ARS outlays are not good predictors of new insect species identification success. In the species introduction equation, the coefficient estimate on agricultural imports is positive, large, and significant, but the coefficient estimate on immigration is positive and insignificant. The coefficient estimate on passenger arrivals by air has an unexpected sign and is statistically significant. The comparison of these results with those for model 3 reveals that adding ARS_t in the species identification Equation (5) and that excluding sea trade from the species introduction Equation (4) yields small changes to the estimated coefficients. During 1983–1998, several significant efforts at identifying new species and combining all known insect databases were undertaken (Frank and McCoy; Knutson et al.; Mattson et al.; Sailer 1983), plausibly resulting in inconsistency of the data with the rest of the record. Better proxies for scientific effort are clearly needed for this analysis, particularly for the most recent years. The log-likelihood value for this model falls to 763.73. Because of the shorter time dimension and the fact that our data on effort and resources are limited to ARS outlays, less variation in the identification rate is explained than previously. (For comparison, model 3 benefited from the significant contribution of sea trade to the species introduction Equation [4].) Despite these data issues, this model is again significant at the 0.1% level.

A Model Using Lessons Learned

Lessons learned are used to construct model 5. It controls for agricultural imports and passenger arrivals during 1882–1990 and incorporates the full extent of the available passenger arrival data. All passenger arrivals are used because models 2 to 4 indicated that air arrivals are more strongly associated with species arrivals (albeit negatively) than immigration. To the extent that air arrivals have accounted for the vast majority of all arrivals since the 1950s, a similar result is expected here:

$$(14) \quad \begin{aligned} \mu_t = {} & \exp(\beta_0 + \beta_1 \cdot agric\ imp_t \\ & + \beta_2 \cdot all\ arriv_t). \end{aligned}$$

Species identification Equation (9) is used. As in the previous specifications, agricultural imports has a large, positive, and statistically significant effect on species introductions, while passenger arrivals have a negative but statistically insignificant effect. Model 5's log-likelihood function value (1,263.63) is larger than the log-likelihood values for model 2 (1,258.93) and model 1 (1,204.88) when the latter models are estimated for the 1882–1900 period, indicating that model 5 explains the most variation in the endogenous variables. Therefore, passenger arrivals appear to be more strongly associated with species introductions than immigration.

Discussion

The results indicate that the explanatory variables selected in our regressions are helpful in explaining species introduction and identifica-

tion rates. With the exception of one coefficient in model 2, all coefficients on economic variables carry the same sign across specifications. This is a nice result suggesting that the model behaves consistently across specifications and does not have multiple solutions. However, some coefficients are not significant in the regressions, or their signs disagreed with our prior expectations. Low degrees of freedom coupled with multicollinearity may be partially responsible. Variance inflation factors indicated the presence of borderline collinearity for model 3. Another explanation for the unexpected signs is that we use only proxies for trade-related variables and have surely omitted a number of relevant variables that would help identify individual coefficients more precisely. The influence of heterogeneous growth rates across insect species and climatic and environmental conditions over time could not be examined, nor could such determinants as invasive species border controls and technological improvements in the transportation industry related to the volume of international travel.

Table 3 summarizes all the coefficients from the previous analysis, as well as the computed effects of marginal changes in each explanatory variable on the annual number of species introductions, on the likelihood of observing a species in a year and, through these two effects, on the annual number of species identifications. Marginal effects in the species introduction Equation (4) are averaged over the 10 most recent years for which we have fully estimated species identifications, that is, introduction years for which we have 10 years with estimated species identification. By averaging, we offset variation in the marginal effects across years due to variation in the explanatory variables, and we obtain a single marginal effect estimate for each variable. We use the most recent years because this provides estimates of present-day effects. In the species identification Equation (5), we evaluate the marginal effect on the probability of identification only in the year of the species introduction (and average them over the 10 most recent years of species introductions) because the probability of observing a species varies across years after its introduction, and it makes little sense to combine years in this case.

The bottom half of Table 3 synthesizes these two sets of results to show the marginal effects of all regressors on the predicted number of species identifications.[7]

The third column in Table 3 summarizes the range of coefficients for each variable, along with their level of statistical significance. Columns 4 and 5 report the range of marginal effects—and their median values—that the coefficients imply, and units of the explanatory variables are reported in the fifth column. Note that coefficient estimate ranges do not translate directly into marginal effects ranges, so the lowest and highest coefficient estimates may not correspond to the lowest and the highest marginal effects. This is because individual models use a different set of explanatory variables and different years. The values of included explanatory variables and their coefficients have an impact on the marginal effects of all other variables.

The results indicate that the annual rate of new species introductions increases 1.1 species every 10 years. The probability of observing an introduced species in the first year after introduction increases 17% every 10 years. Because our data cover only 1,097 insect species of the approximately 4,600 insect species thought to exist in the United States (Pimentel et al. 2000, 2001), or 24%, it is likely that 1.1 species underestimates the true introduction rate per 10 years. Assuming that nonindegenous insect species, which are not in our database, had the same propensity to arrive and were introduced under the same conditions and subject to the same factors as the included species, linear extrapolation suggests a growth rate of 4.7 species every 10 years. A \$1 billion (1.7%) increase in agricultural imports increases the annual rate of new species introductions 0.78 species (3.25 species when extrapolated to all known nonindegenous insect species). A 100-kiloton (9.1%) increase in sea trade increases the

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[7] In this case we allow species observation in all 10 years after species introduction. We average the marginal effects over the 10 most recent years of species introductions for which we have fully estimated species identifications.

Table 3. Marginal Effects Implied by the Coefficients in All Models on the Number of Annual Introductions, on the Probability of Observation in the Year of Arrival, and on the Number of Annual Identifications

| Coefficient	Variable	Coefficient Range	Marginal Effect Range	Median Marginal Effect per Unit Change in Variable
Marginal effects on the number of annually introduced species				
β_0	Introduction rate constant	−2.737*–1.011*	—	—
β_1	Introduction rate t	1.330*	0.000–2.218	1.109 per 10 years
β_1	agric imp$_t$	52.584*–165.233*	0.436–1.022	0.776 per $billion
β_2	all arriv$_t$	−14.202	−0.165	−0.165 per million persons
β_2	immigr$_t$	−0.102–1.219	−0.113–0.738	0.142 per 100,000 persons
β_3	air arriv$_t$	−74.571* to −61.492*	−0.339 to −0.270	−0.305 per million persons
β_4	sea trade$_t$	2.085**	0.871	0.871 per 100 kilotons
Marginal effects on the probability of species observation in the year of arrival				
γ_0	Identification rate constant	−628.398* to −0.906	—	—
γ_1	Identification rate t	30.410*–109.957*	0.000–0.342	0.171 per 10 years
γ_1	ARS outlay$_t$	−3.829	0.000	0.000 per $100 million
γ_2	Identification rate $(t–s)$	−3.373–567.973*	—	—
Marginal effects on the number of annually identified species				
β_0	Introduction rate constant	−2.737*–1.011*	—	—
β_1	Introduction rate t	1.330*	−1.618–2.218	−0.791 per 10 years
β_1	agric imp$_t$	52.584*–165.233*	0.627–1.160	0.991 per $billion
β_2	all arriv$_t$	−14.202	−0.245	−0.245 per million persons
β_2	immigr$_t$	−0.102–1.219	−0.146–0.711	0.205 per 100,000 persons
β_3	air arriv$_t$	−74.571* to −61.492*	−0.388 to −0.327	−0.358 per million persons
β_4	sea trade$_t$	2.085**	1.253	1.253 per 100 kilotons
γ_0	Identification rate constant	−628.398* to −0.906	—	—
γ_1	Identification rate t	30.410*–109.957*	−1.618–2.218	−0.791 per 10 years
γ_1	ARS outlay$_t$	−3.829	0.036	0.036 per $100 million
γ_2	Identification rate $(t–s)$	−3.373–567.973*	—	—

Note: The dependent variables are the annual number of species introductions, the likelihood of observing a species in the year of introduction, and the number of species identifications. All monetary variables are deflated to 2003 dollars using Sahr.
* Coefficient is significant at the 0.1% level.
** Coefficient is significant at the 1% level.

annual rate of new introductions 0.87 species (3.65 species extrapolated). A 100,000 (7.7%) increase in immigrants per year increases the annual introduction rate 0.14 species (0.60 species extrapolated). However, a 1 million (1.7%) increase in arrivals of all passengers per year reduces the annual introduction rate 0.17 species (0.69 species extrapolated). Air passengers, which starting in the 1950s took over the vast majority of international travel, are predicted to lower annual introductions by 0.31 insect species (1.28 species extrapolated) for a 1 million (1.7%) increase in arriving passengers. A $100 million (9.1%) increase in
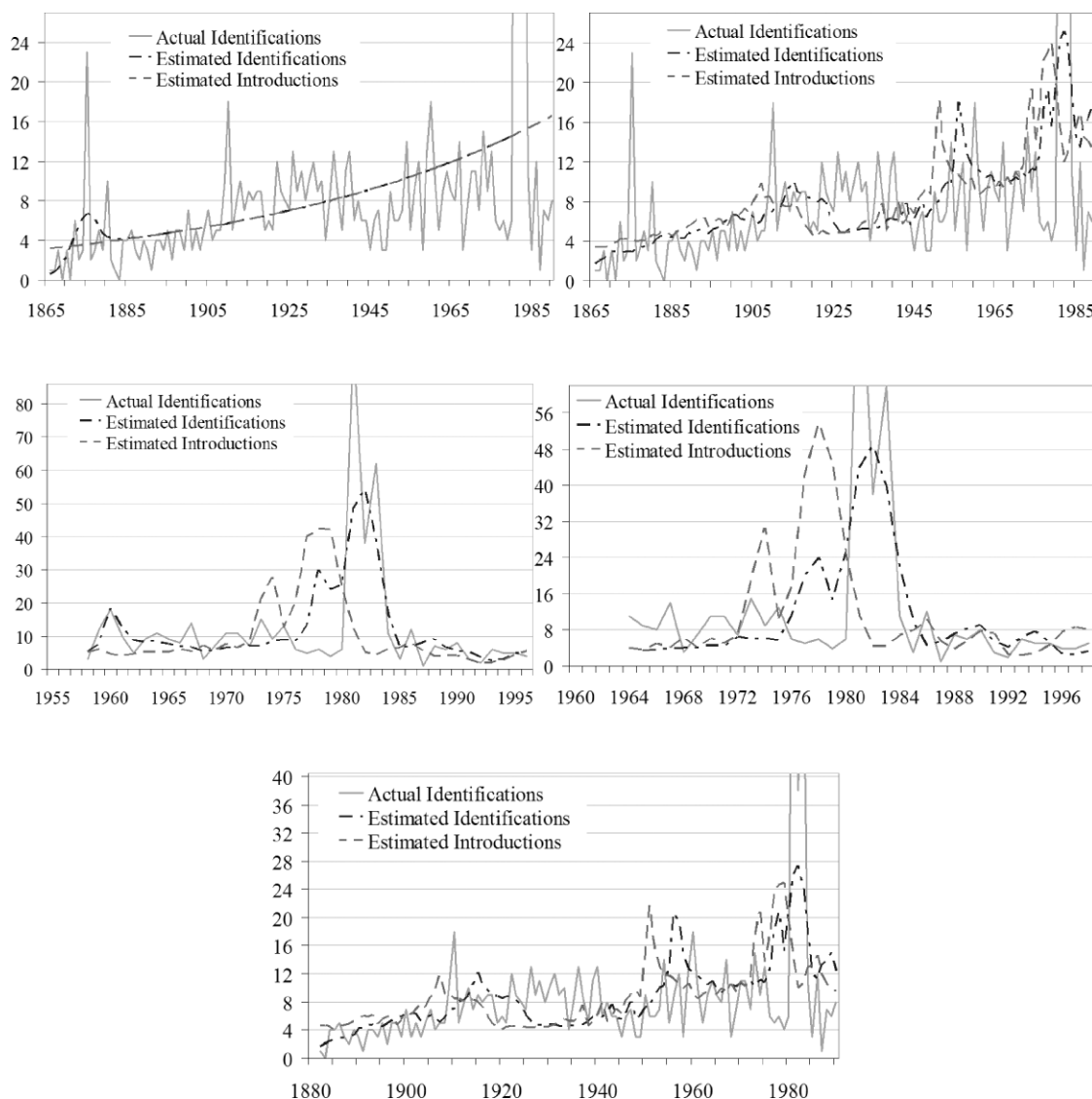
Figure 1. Estimated Annual Introductions and Actual and Estimated Annual Identifications across All Models

ARS outlays is predicted to increase the annual rate of new insect species identifications by 0.04 species (0.15 extrapolated). The small impact of ARS outlays is likely due to the broadness of ARS's functions.

The combined impacts of the marginal effects in the species introduction Equation (4) and species identification Equation (5) are reported at the bottom of Table 3. These effects are for the most part slightly larger in magnitude than the marginal effects on the species introductions because the number of identifications exceeds the number of estimated introductions in three out of our five models. The majority of the estimates in Table 3 are statistically significant, but their impacts on the introduction and observation rates are smaller and sometimes indistinguishable from zero. These estimates imply that an enormous change would have to occur in the explanatory variable to affect the species introduction and observation rates noticeably.

For each model, Figure 1 plots estimated introduction and identification rates against
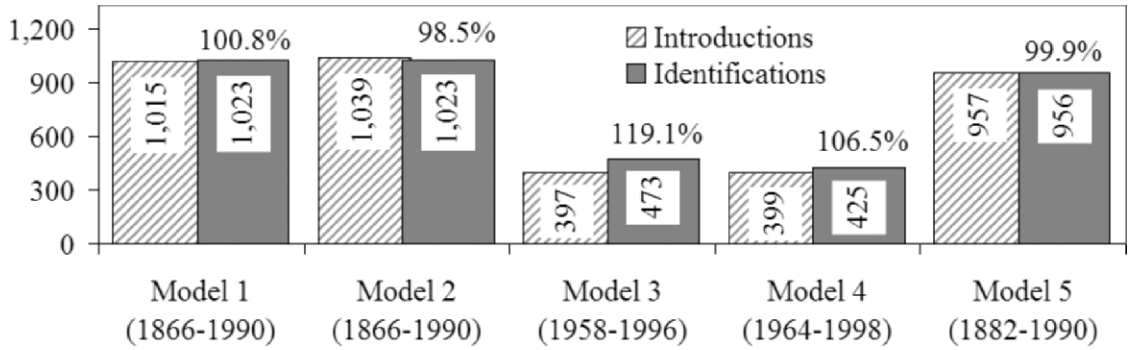
Figure 2. Estimated and Actual Numbers of Identifications, Cumulative over the Time Period of Estimation, across All Models

actual identifications, and Figure 2 compares estimated numbers of introductions to actual numbers of identifications. Percentages of estimated introductions that are identified are also reported. Generally, estimated introductions are similar to actual identifications. Models 1 and 5 predict the number of introductions within 1% of the number of identifications. Model 2 predicts that the number of identifications falls short of the introductions by only 1.5%. Models 3 and 4 estimate that species identifications exceed introductions by 6.5% to 19.1%, implying that in the last four decades of the twentieth century, scientists identified 26 to 76 more species than the number of species introduced during that period.

Using Figure 2, we may predict that the number of unidentified insect species in the United States accounts for up to 1.6% (as in model 2, 1,039/1,023 − 1) of the currently known stock. Compared to the 4,600 nonindegenous insect species identified in the United States, this would imply 72 unidentified species. Williamson and Fitter and Mooney and Cleland estimate that 10% of imported species appear in the wild, 10% of introduced species become established, and 10% of established species become invasive. Following this rule of thumb and assuming that 72 unidentified insect species have appeared in the wild, we may infer that 720 species were introduced into the United States undetected, that seven may become established, and that one of these insect species may become invasive.

Table 4 shows the estimated mean time lags between species introductions and identifications across our model specifications along with the standard deviation of the mean drawn from a geometric distribution.[8] Note that the mean time lag until identification is computed for all insect species taken together; individual species may have longer or shorter identification time lags depending on characteristics and conditions (Carey; Reichard and White). The reported times until identification may also vary over time, as can be seen from the varying distances between the peaks in introductions and identifications in the subfigures of Figure 1.

Conclusions

In this study we attempt to examine the determinants of introductions of insect species into the United States. Because introduction

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[8] The mean and variance of the waiting time until identification of a species that was introduced in period s are computed as

$$E(w_s) = \sum_{i=s}^{t} \left[(i - s + 1) \cdot \overline{\pi}_{is} \cdot \prod_{j=s}^{i} \left(1 - \overline{\pi}_{(j-1)s}\right) \right]$$

$$V(w_s) = \sum_{i=s}^{t} \left[(i - s + 1)^2 \cdot \overline{\pi}_{is} \cdot \prod_{j=s}^{i} \left(1 - \overline{\pi}_{(j-1)s}\right) \right],$$

where t are species-observation years, in this case up to $t = 10$. To get the mean waiting time for species introduced in all years, we average $E(w_s)$ over all species-introduction years s for which we have the full 10 years of identification data.

Table 4. Mean Time Lag between Introduction and Identification across All Models

Model	Mean Time Lag (Years)	Standard Deviation	Variance
1	1.31	1.82	3.32
2	7.75	7.99	63.90
3	5.89	6.16	37.89
4	4.80	4.83	23.34
5	7.71	7.95	63.18

Note: The mean waiting time is computed for each introduction year s and then averaged over all s for which there are all 10 years of identification data available. The standard deviation and variance are computed for the geometric distribution.

and identification rates differ, we use a maximum likelihood estimation method to control for time lags and the probabilistic relationship between these events. We show that a limited number of variables can explain a great amount of variation in introduction and identification rates. The most significant contributor to the introduction of nonindegenous insect species appears to be imports of agricultural goods. A $1 billion increase in agricultural imports is estimated to increase introductions as much as one new species per year. The volume of sea trade also has a significant positive effect, at 0.9 new species per year per 100-kiloton increase. Immigration appears to cause a modest, statistically insignificant number of new species arrivals.

There is counterintuitive evidence regarding the impact of passenger arrivals, especially airborne passengers, on species introductions. This may be due to the difficulty of distinguishing their impact from those of other trade-related variables, omitted correlated variables (such as arrivals by sea and by land, which were to a large degree replaced by air arrivals), and, to some extent, measurement errors. Air transport may also be less susceptible to insect contamination than other means of transport omitted in this analysis. We also find that currently available proxies for public effort are weak predictors of the probability that new species will be observed after their introduction. Further research would focus on better proxies for the level of scientific effort

to identify new species and on distinguishing the individual effects of these efforts—exclusion, mitigation and information gathering—in order to identify the historic significance of prevention efforts and guide policymakers in the development of efficient control programs in the coming years.

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