The accelerating rates of international trade, travel, and transport in the latter half of the twentieth century have led to the progressive mixing of biota from across the world and the number of species introduced to new regions continues to increase. The importance of biogeographic, climatic, economic, and demographic factors as drivers of this trend is increasingly being realized but as yet there is no consensus regarding their relative importance. Whereas little may be done to mitigate the effects of geography and climate on invasions, a wider range of options may exist to moderate the impacts of economic and demographic drivers. Here we use the most recent data available from Europe to partition between macroecological, economic, and demographic variables the variation in alien species richness of bryophytes, fungi, vascular plants, terrestrial insects, aquatic invertebrates, fish, amphibians, reptiles, birds, and mammals. Only national wealth and human population density were statistically significant predictors in the majority of models when analyzed jointly with climate, geography, and land cover. The economic and demographic variables reflect the intensity of human activities and integrate the effect of factors that directly determine the outcome of invasion such as propagule pressure, pathways of introduction, eutrophication, and the intensity of anthropogenic disturbance. The strong influence of economic and demographic variables on the levels of invasion by alien species demonstrates that future solutions to the problem of biological invasions at a national scale lie in mitigating the negative environmental consequences of human activities that generate wealth and by promoting more sustainable population growth.

climate | economy | exotic plants and animals | geography | prediction

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A recent compilation of the most up-to-date information on alien species in Europe (2) provides an excellent opportunity to perform, at a continental scale, analyses aimed at identifying general predictors of invasion that are applicable to a wide range of taxa in terrestrial and aquatic environments. This data set is unique in covering alien plants, fungi, and animals, which enabled us to analyze both the joint and net effects of macroecological and macroeconomic explanatory variables shaping invasions, while taking into account spatial autocorrelation. Specifically, this paper aims to answer the following two questions: (i) What are the main factors that determine the level of biological invasions, defined as the number of alien species, in European regions? (ii) What is the relative importance of geographicaI, climatic, land-cover related factors, compared with economic and demographic variables?

However, an obvious problem associated with attempts to explain current levels of invasions by economic data stems from the fact that the economic data are usually recent, whereas the lists of established alien species result from invasion processes that have occurred over several centuries (26). Some papers have used measures of a current flow, such as gross domestic product (GDP) (23, 27, 28), human-development index (HDI) (21), or trade flows (15–17) to explain the cumulative level of invasions drawn over several centuries. However, it is inappropriate to use current economic indicators as the measure of historical processes. Because there is a lack of reliable historical economic data on such a large temporal and spatial scale to which cumulative invasions could be related, an appropriate independent economic variable for such analysis is one based on a stock of capital, which reflects the cumulative effect of historic investments, rather than on capital flow. To overcome these problems we used wealth, an economic variable that characterizes current economic prosperity of European regions, as the cumulative outcome of the economic history of that region, reflecting more accurately an economic development over a longer time span (29). This enabled us to relate the cumulative stocks of alien species to measures of cumulative economic prosperity.

Results
A minimal adequate model (MAM) of the effects on alien species explained 25.1% of variability across all taxa. Most variance was explained for plants (91.0%) and bryophytes (78.9%) and the least for insects (18.0%) and fungi (24.8%). The explained variance for the remaining taxonomic groups was: aquatic invertebrates 51.0%, reptiles 49.1%, birds 39.6%, and mammals 38.9%. The relative effects of variables shaping the invasions by the individual taxonomic groups (Fig. 1) indicate that the regional patterns are rather complex, but some insights can be obtained by linking them to the pathways of introduction to Europe (35). The overwhelming effect of human factors, i.e., wealth and demography, found for several taxonomic groups translates to human activities responsible for enhancing biological invasions (36). For example, it can be related to the pet trade (resulting in deliberate releases of birds and mammals) (33, 35, 37) or linked with unintentional introductions that are associated with movement of contaminated commodities such as agricultural produce (insects, fungi) and aquaculture stocks (aquatic invertebrates). The invasions by bryophytes are primarily determined by climate due to susceptibility of this group to environmental conditions in the region of introduction (38) and their relatively low importance as either a commodity (ornamentals) or a contaminant of a commodity (timber). The significant although small net effect of climate on mammals suggests that this group is also constrained by unsuitable local climatic conditions, which may be due to frequent opportunistic releases and escapes of pets from captivity, sometimes in regions poorly compatible with their own climatic requirements (39). For example, Mongolian gerbils (Meriones unguiculatus) are commonly kept as pets in the United Kingdom and although escapes are common and feral populations have been recorded, these populations do not persist for many years. The complex pattern we found for plants might reflect that the relatively few species introduced deliberately for economic purposes, e.g., forestry and agricultural species, have a higher probability of establishment than species from the considerably larger pool of introduced ornamental species that are less frequently well matched to the local climate (14).

Finally, why the factors included in our study failed to predict the level of invasion by amphibians in Europe is difficult to explain and may also reflect the small sample size; for fish the reason may be historical. The nonsignificant effect of wealth and demography in our models for fish (see also ref. 40) probably reflects that introductions have been a massive phenomenon across Europe for stock enhancement and sport fishing (23, 41). As a result, the pattern of fishery wealth (fishery income as the share of total income) is likely to be different from the overall pattern of national wealth. Indeed, densities of alien fish were also found more difficult to predict than those of plants and birds across counties in the United States (42, but see refs. 23, 43).
The most important conclusion is that human population density and wealth appear to be the major statistically significant predictors in the majority of models when analyzed jointly with environmental factors such as climate, geography, and land cover. Therefore it is not surprising that previous studies using only economic factors successfully predicted the numbers of alien plant species in the United States and Canada (15, 22). Our results, however robust, need to be interpreted with caution because the economic variables are not direct causal determinants of the invasion process but reflect the intensity of human activities and integrate the effect of factors that directly determine the outcome of invasion such as propagule pressure (11), pathways of introduction (35), intensity of disturbance (28, 44), and eutrophication (45, 46). However, the precise mechanisms are difficult to disentangle using current data (47), because historical data on where and when an individual species first naturalized are still rather scarce and often uncertain. Therefore, relating the current, cumulative levels of established alien species with an economic measure of cumulative historic investments such as the capital stock, and with current population density in the regions studied seems to be a more credible approach (29).

That wealth and population density are most important does not mean that geography, climate, and land cover have no role in the outcome of invasions. A few studies have considered both environmental and economic factors at the same time (12, 16), and without statistical analysis aimed at determining net effects of individual variables and their relative importance. Our paper shows that effects of the former are overwhelmed by that of human variables. This implies that the effects of noneconomic variables may be overestimated in analyses of factors shaping macroecological patterns of invasions over large spatial scales (48). This raises questions regarding the validity of studies that, in the absence of economic data, concluded that geographic factors are the main determinants of variation in the numbers of alien species at regional and continental scale (9, 10, 49). Therefore, future studies should not ignore the effects of human-related factors when testing the effect of underlying factors and predicting the distribution of alien species (17, 22, 50).

Fig. 1. Partitioning of the variance of standardized alien species numbers in each region adjusted for the effect of area among classes of explanatory variables representing insularity (as the only fitted geographic variable), human factors (including wealth and human population density) and climate. Model for all taxa and for individual taxonomic groups, ranked according to explained variance, are presented. Only the classes of variables for which their joint effects appear significant \((P < 0.05)\) are shown (i.e., three classes of variables for all taxa, bryophytes, plants and reptiles, and two classes for birds, mammals and aquatic invertebrates). Intersections of circles in the Venn diagrams represent the variance jointly explained by two or three classes of variables; their negative fractions are given by the correlation structure of the explanatory variables, in which direct and indirect positive and negative effects of the individual variables are combined (ref. 70, p. 533). The rectangles represent 100% of the variance, of which \([h]\) (for taxa having three classes of variables with significant joint effects) or \([d]\) (for taxa having two such classes) is the unexplained part. Only the net effects \((a, b\) and \(c)\) for taxa having two classes of variables have significant joint effects, and \((a)\) and \((c)\) for taxa with two such classes can be tested statistically; of these, significant \((P < 0.05)\) net effects are underlined. Intersections \((d)–(g)\) for taxa with three classes and \((b)\) for taxa with two classes cannot be tested. Note that there is no variation partitioning for insects and fungi because all variance in these taxa was explained by the explanatory variables from only human factors (29.5% for insects and 24.8% for fungi) and that no explanatory variable appeared significant for amphibians and fish.
The strong influence of economic factors on the level of invasion by alien species demonstrates that future solutions to the problem of biological invasions will be a considerable challenge (22, 51). How can this knowledge be used to address these problems? The growth in the volume and diversity of trade has increased the frequency of new introductions and hence the probability that an introduced species will spread and have an impact (1, 50, 52). Identifying the responsibilities of the key actors involved in trade and targeting legislation appropriately may go some way toward managing invasions (35). Where commodities themselves pose a risk either as deliberate releases or escapes e.g., pets, ornamental plants, new crops, etc., a possible solution would be to ensure the market price also reflects the likelihood and subsequent cost should the species prove to be invasive (51). Yet, the main impediment to adopting this principle is that the World Trade Organization and the international agreement regulating international trade (GATT) have no effective mechanisms by which to internalize the invasion externalities of international trade (51). This is especially true for unintentional introductions such as contaminants and stowaways (35) for which international trade (GATT) have no effective mechanisms by which to internalize the invasion externalities of international trade (51). This is especially true for unintentional introductions such as contaminants and stowaways (35) for which higher tariffs might be required to cover the cost of monitoring and inspecting high-risk pathways (53). However, tariffs may be misused as protectionist tools and disadvantage many developing countries for which the problems of contaminants and stowaways may be more difficult to manage (54). Although an indirect function of trade, the increasing development of transport infrastructures provides corridors for the spread of alien species and increasingly the environmental impact assessment of such projects should address their potential role in biological invasions and mitigate these invasions where possible (1, 35).

Nations do not have a good track record in forsaking future economic prosperity for environmental benefits. As a future challenge, there is a critical need for a multidisciplinary effort to identify the specific economic pressures that are the most proximate causes of the alien species problem (e.g., factors leading to high propagule pressure) and that could serve as indicators that can be mitigated by policy makers to prevent invasions (35). Only if the true determinants are identified, will it be possible to predict and manage alien species invasions adequately without adverse effects on other economic sectors. A much higher precision for predicting invasions will undoubtedly help current attempts in Europe to design management strategies for alien species (3, 55, 56).

Methods

Data Collection. The present paper is based on numbers of naturalized (established) alien species that form self-reproducing populations in the wild without direct intervention of humans and that were introduced to Europe after 1500 A.D. (hereafter termed “alien”; see ref. 57). Data on numbers of alien species were collected for 55 countries, administrative regions, or major islands (hereafter termed “regions”; Table S1) and 10 taxonomic groups, including vascular plants (n = 20, number of regions for which the data were available), bryophytes (n = 32), fungi (n = 51), mammals (n = 45), birds (n = 53), amphibians (n = 26), reptiles (n = 38), terrestrial insects (n = 53), fish (n = 38), and aquatic invertebrates (n = 34) (see Table S1 for data sources). Two groups, fish and aquatic invertebrates, occur in inland waters, the remaining eight primarily in the terrestrial environment. Although the coverage of particular taxonomic groups differed among regions (Table S1), the data, collated by the DAISIE project (2), provided a sound basis for analyzing the level of invasion across Europe (sensu refs. 5, 7).

Thirteen explanatory variables were provided to each region and divided into four classes related to environmental (I-III) and human (IV) factors. (i) Geography: (i) insularity (island versus continent; yes/no); (ii) latitude and (iii) longitude (taken as region mid points); (iv) total area of the region; (v) total surface area of inland waters. (ii) Climate, based on data from 1970 to 2000 at 10 arc-min pixel resolution (58) or on data of similar resolution taken from www.worldclim.org (59) for regions outside continental Europe: (vi) mean annual precipitation; (vii) mean annual temperature; (viii) continentality expressed as the difference in mean July and January temperature. (iii) Land cover: (ix) number of habitats, expressed as the number of CORINE land-cover classes (60, version 8/2005 obtained from the European Environment Agency); (x) habitat heterogeneity measured as Gini coefficient of equitability of habitat distribution (61), based on the area of individual CORINE land-cover classes in the region. (IV) Human factors, include both economic and demographic variables: (xi) human population density per km² (62); (xii) road density (km/km²), taken from ref. 63) and (xiii) national wealth estimates, based on produced, natural, and intangible capital (62).
Statistical Analysis. Response variables were the numbers of alien species in each region. These numbers were square root + 0.5 transformed (64) to normalize and to standardize to zero mean and variance of one, separately for each taxonomic group. This made it possible to compare the level of invasion across taxa as it varied across two orders of magnitude (Table S1). To account for species–area relationships, the transformed and standardized numbers were regressed on log region area and a MAM was established. This MAM described significant (P < 0.05) group-specific slopes on area. Pearson’s standardized residuals (66) from this MAM were used as the response variable (i.e., describing standardized alien species numbers adjusted for the effect of area) fitted separately for each taxonomic group and across all groups.

Of the geographic variables only insularity was directly used as an explanatory variable; the other geographic variables were used to standardize the response variable or to test for effects of spatial autocorrelation. As we were interested in generic trends of invasions across all taxa corrected for area (see above), the total region area was also used for groups found in aquatic environments because there was a very close correlation between the total area of the region and that of its inland water surface area (Pearson’s product-moment correlation = 0.87; Spearman’s rank correlation = 0.89). The midpoint of latitude and longitude for each region was used to test for geographic variables.

All other variables were included as explanatory variables. In linear models, human population density was log transformed before analyses to normalize the data, and all covariates standardized to zero mean and unit variance to achieve their comparable influence. Using the standardized values, collinearity was checked by calculating tolerance values among all of the explanatory variables (67).

To establish MAMs, backward simplifications of full models were performed (68). Because it was impossible to fit the full models directly due to a high number of explanatory variables, the analyses were first run within the factors/ classes of variables related to geography, climate, land cover, and human factors (67). To achieve the common MAMs, the model simplifications were then repeated on all significant explanatory variables and their interactions, which were established by these previous analyses. All chosen variables characterize geography, climate, land cover, and human factors were checked for all possible mutual one- and two-way interactions. All MAMs were also checked for normality and heteroscedasticity of the residuals (69). Their explained variance was expressed by $R^2_{\text{adj}}$ (%), taking into account sample sizes and number of predictors (i.e., $\text{eq.}$, 67).

For each taxonomic group, variance partitioning (70) was used to split the variance in alien species richness into the net effects of each class of variables and their joint effects. Before the partitioning, stepwise selection procedure was based on Akaike Information Criterion were applied, separately on each class of explanatory variables (70) to choose the appropriate variables from each class. This stepwise selection differed from previous simplifications of full models, because the simplification did not include interactions among the explanatory variables. The variance partitioning then proceeded on classes of variables, selected by the stepwise procedure. Net variations due to the individual selected classes, and variations related to their joint effects, were obtained by subtraction, which were made on the basis of adjusted coefficients of explained variance $R^2_{\text{adj}}$ (following ref. 70). Statistical significance of individual parts of the variance was calculated by permutation tests (70).

Regression trees (30, 71, 72) were used to provide understandable and generally interpretable results of interactions between explanatory variables of MAMs. The trees were constructed by repeatedly splitting the response variables using binary recursive partitioning in CART v. 6.0 (71, 73). To find the best tree, a sequence of nested trees of decreasing size, each being the best of all trees of its size, was grown, and their resubstitution relative errors, corresponding to residual sums of squares, were estimated. Tenfold cross-validation was used to obtain estimates of cross-validated relative errors of these trees. These estimates were then plotted against tree size, and the best tree chosen both on the basis of the minimum cost tree rule, which optimizes the cross-validated error (the default setting in CART v. 6.0; ref. 73), and on the one-SE rule, which minimizes cross-validated error within one SE of the minimum (71). Following ref. 72, a series of 50 cross-validations was run, on the basis of each rule, and the modal (most likely) single tree chosen for description. To prevent missing explanatory variables having an advantage over complete explanatory variables, full trees were penalized in proportion to the degree to which they were missing and treated by back-up rules that closely mimicked the action of the primary splits (71, 73). Total variance explained by the best single tree was calculated as $R^2 = 1 – \text{resubstitution relative error}$. The quality of each split was expressed by improvement, corresponding to proportion of the total sum of squares explained by the tree at each node.

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Supporting Information

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SI Text: Spatial Autocorrelation

SI Methods. To test whether the models violated the basic assumption of the independence of errors of the observations due to spatial autocorrelation (1–3), the response variable entering the analyses, i.e., standardized alien species numbers in each region adjusted for the effect of area, and the residuals of the individual minimal adequate models (MAMs), were evaluated by Moran’s I correlograms (4, 5) in SAM 3.0 (6).

Under the null hypothesis of no spatial autocorrelation, meaning that data collated from regions at some distances apart do not exhibit more similar/dissimilar records than expected by chance (2, 7), I has an expected value near zero, with positive and negative values indicating positive and negative autocorrelation, respectively. Because I does not vary strictly between −1 and +1, we standardized I by dividing by its maximum attainable value to yield $I_{std}$ which can be interpreted as a spatial autocorrelation index, enabling us to compare values of I among models (6, 7). Each distance class among regions was defined on the basis of decimal degrees of latitude and longitude, taken as the midpoint of each region from which the data were collated. These decimal degrees were converted into geodesic surface distances (km), assuming that the Earth is spherical, and taking into account the actual polar flattening of the Earth and the equatorial bulge. To ensure that the tests had approximately the same power across all distance classes, the tests were done with each distance class having a different range, but the number of sampling points being roughly the same (5, 6). The number of sampling points in each distance class ranged between 15 and 48 for the individual taxa and between 1,929 and 1,997 in tests across all taxa.

Bonferroni-corrected significance level ($P < 0.05$) was used to check whether the correlogram contains at least one autocorrelation statistic, which is significantly different from zero, and two-tailed sequential Bonferroni corrections for identifying the individual distances that are significantly autocorrelated (5).

Because all tests for significant Is, including the response variable entering the analyses, were tests of residuals, testing of their significant departures from null expectations on spatial independence followed Lichstein et al.’s (7) permutations on ordinary least square residuals. These tests are appropriate for small samples and do not assume a normal sampling distribution of I. They were done based on a distribution of 1,000 values, which included 999 random permutations and the reference value (the observed value for which the test is desired; ref. 5). Moran’s I for the comparable effects of alien species entering the analyses often violated the condition of second-order stationarity (5) and as such, should not be tested statistically (5). Following ref. 7, in these cases, values of Is are interpreted just as indicators of the presence or absence of spatial patterns, which is an acceptable use for descriptive purposes (5).

SI Results

For alien species numbers adjusted for the effect of area entering the analyses (Figs. S1 and S2A), there were tendencies for significant positive autocorrelations for neighboring regions and negative ones for distant regions. This pattern thus resembled a linear gradient with the similarity decreasing with increasing distance. However, for the individual taxa, residuals of all models had all of the spatial autocorrelations removed (Figs. S2B). Across all taxa (Fig. S1B), there remained a small although significant positive autocorrelation at the distance of about 150 km, and negative one at the distance about 2,200 km. However, the overall linear gradient of decreasing similarity with increasing distance was also reliably removed. The explained variability of models describing the adjusted alien species numbers thus did not, or only slightly, violate the statistical assumption of independently and identically distributed errors. This means that the explanatory variables were properly included in the models and adequately measured their effects on alien species.


Pylek et al. www.pnas.org/cgi/content/short/1002314107
Fig. S1. Autocorrelation statistics for adjusted alien species numbers entering the analyses (A) and for residuals of their minimal adequate models (B), plotted against distance classes (km) represented by geographic midpoints of regions in which the data on alien species were collated. Autocorrelation statistics are expressed as standardized Moran’s I correlograms, which vary between +1 and –1; they have expected value near zero for no spatial autocorrelation, with negative and positive values indicating negative and positive autocorrelation, respectively. Each point on y axis represents the value of I calculated from all possible pairs of sample locations that are separated by the lag distance intervals on the x axis. Black squares indicate values of I that are significantly larger than the value expected under the null hypothesis of no autocorrelation (two-tailed test with α = 0.05 adjusted using progressive Bonferroni correction); white squares are not significantly larger than the null expectation. Results across all taxa.

Fig. S2. (Continued)
Fig. S2. (Continued)
Fig. S2. Autocorrelation statistics for adjusted alien species numbers entering the analyses (A) and for residuals of their minimal adequate models (B), plotted against distance classes (km) represented by geographic midpoints of regions in which the data on alien species were collated. Results for the individual taxa, ordered according to the total variance explained by the individual minimal adequate models. NS for B are taxa with statistically insignificant minimal adequate models. Otherwise as in Fig. S1.
Table S1. Numbers of naturalized (established) alien species in 55 European countries/regions analyzed

<table>
<thead>
<tr>
<th>Region</th>
<th>Vascular plants</th>
<th>Bryophytes</th>
<th>Fungi</th>
<th>Mammals</th>
<th>Birds</th>
<th>Reptiles</th>
<th>Amphibians</th>
<th>Fish</th>
<th>Terrestrial insects</th>
<th>Aquatic invertebrates</th>
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<td>8</td>
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<td>0</td>
<td>11</td>
<td>17</td>
<td>265</td>
<td>50</td>
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Empty cells indicate that data are not available. Data sources (see www.europe.aliens.org for species lists): vascular plants (1); bryophytes (2); fungi: various (see ref. 3 for details); mammals: various (see ref. 4 for details); birds, reptiles, and amphibians: various (see ref. 5 for details); fish, aquatic invertebrates (6); and terrestrial insects: various (see ref. 7 for details). State names refer to mainland.


