Predicting Invasions of Woody Plants Introduced into North America

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Abstract: *Plant species continue to be introduced in North America for various purposes. If the trend continues, it is probable that some will escape cultivation and become invasive in native ecosystems. We present a retrospective analysis of several structural, life history, and biogeographical attributes of woody plants introduced in North America to determine which traits characterize species that have and have not invaded. Predictive models derived from discriminant analysis correctly classified 86.2% of the species in cross-validation, whereas those derived from classification and regression trees classified 76% correctly. From these models we created a hierarchical predictive tree that allows the user to divide species into three categories: admit (low risk of invasiveness), deny admission (high risk of invasiveness), or delay admission for further analyses and/or monitor intensively (risk cannot adequately be assessed based on only the included attributes). We recommend that species that are highly invasive elsewhere not be allowed into the U.S. and that a more conservative introduction policy using a hierarchical predictive method be employed.*

Predicción de Invasiones de Plantas Leñosas Introducidas a Norteamérica

Resumen: *Especies de plantas continúan siendo introducidas a Norteamérica para diversos motivos. De continuar la tendencia, es probable que alguna escape y se vuelva invasiva en ecosistemas nativos. Presentamos un anàlisis retrospectivo de varios atributos estructurales, biológicos y biogeográficos de plantas leñosas introducidas a Norteamérica para determinar los rasgos característicos de las especies que han invadido y de las que no han invadido. Los modelos predictivos derivados de análisis discriminatorio clasificaron correctamente al 86.2% e las especies en validación cruzada, mientras que los modelos derivados de dendrogramas de clasificación y de regresión clasificaron correctamente al 76%. A partir de estos modelos creamos un dendrograma predictivo jerárquico que permite al usuario dividir a las especies en tres categorías: admitir (bajo riesgo de invasividad), negar admisión (alto riesgo de invasividad) o retrasar admisión para análisis posterior y/o monitoreo intensivo (el riesgo no puede evaluarse adecuadamente sólo con base en los atributos incluidos. Recomendamos que no se permita la entrada a E.U.A. de especies que son altamente invasivas en otras partes y que se aplique una política de introducción conservadora basada en un modelo predictivo jerárquico.*

Introduction

The rate of introduction of non-indigenous plant species into North America is not likely to decline in the coming years. Agriculturists, horticulturists, and foresters continue to introduce new plant species for commercial purposes, and other species reach North America by accident. Most intentionally introduced species remain in their cultivated settings, but some invade natural areas. Of the 235 woody plant species that have naturalized in North America, 201 or 85% were introduced primarily for the landscape trade (both ornamental and functional landscaping, such as erosion control), and 34 (14%) were introduced primarily for agriculture or production forestry (Reichard 1994).

In the past such introductions were made solely on the basis of attributes of the species that served the purpose of the introductions. Little or no concern was given to potential negative effects such as invasiveness.

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Today, there is an increasing awareness of the environmental problems caused by non-native invasive species (Vitousek et al. 1987; U.S. Congress 1993) yet the mechanisms to exclude species from entry into the United States based on their invasive potential are largely ineffective (Westbrooks 1991).

In the United States the Federal Noxious Weed Act, passed in 1974, provides the main authority for the restriction of "weeds." It currently prohibits the import of 94 listed species. The purpose of listing is to restrict movement of a known problem species, with action taken only after a species is shown to present a significant risk. The Act does not require the evaluation for invasive potential of "new," intentionally introduced species at the time of introduction. The Act has been less than successful in preventing introductions of plant species capable of invading natural ecosystems for several reasons, primarily because it has been applied mostly to agricultural pest plants and because funding is inadequate. It has also been applied to too few species; at least 750 species meeting the Act's definition of noxious weeds still remain unlisted (U.S. Congress 1993).

There are four possible policy strategies that can be used for the importation and screening of invasive potential of plant species (Ruesink et al. 1995): (1) all species can be admitted unless proven to be invasive and thus specifically prohibited (a "dirty list" approach); (2) all species can be prohibited unless known to be non-invasive and listed as such (a "clean list" approach); (3) each species can be tested for invasiveness before making a decision regarding entry; or (4) an informed estimate of invasive potential can be made about a species based on available information about other invasive species. Currently, the United States, in accordance with the Federal Noxious Weed Act, allows all plants into the country as long as they are not on a brief list of "dirty" species that are known to harbor agricultural pests or are known weeds. This is consistent with strategy number one above. Because there are very few restrictions limiting what can be introduced, botanical gardens, nurseries, agricultural organizations, and individuals can import plants and exchange seeds at will. The dirty list approach is commonly used to prevent interstate transport of harmful species, mostly fish and wildlife, but there is a growing realization that more systematic and formal methods need to be developed (U.S. Congress 1993). Changing to a "clean" (i.e., allowed) list approach by which all species would be banned from importation unless they could be proven to be pest-free and lacking in weed potential is one such method; species could be placed on the clean list and no further reviews would be needed for subsequent introduction of those species. The clean list approach is analogous to the U.S. Food and Drug Administration's regulatory system for approving drugs for human use. The clean list approach shares, with the third alternative listed, the need to hold all plant material with unknown invasive potential in quarantine for an extended period of time. A long holding period is a politically and legally unfeasible, as well as expensive, solution for goods in trade. Holding the species in quarantine for an extended period of time to evaluate invasiveness may reveal little anyway, unless it is held for decades; many invasive species have a considerable "lag period" between introduction and commencement of invasion (Scott & Panetta 1993; Hobbs & Humphries 1995). This leaves the fourth option, to develop predictive methods based on what is known about invasive species that will allow the evaluation of a species invasive potential prior to introduction. Approval for a species would be held until it was determined to have a low or high potential for invasiveness and could be placed on a clean or dirty list, with some questionable species perhaps held for further determination of invasive qualities. This would provide a more conservative approach and therefore provide more protection for the environment than under current laws and would be fair to those wishing to introduce species by allowing at least some species into the country quickly.

The goal of this project is to determine whether there are traits of plants that are positively correlated with invasiveness, whether or not they are related to the actual underlying causative characteristics. We use a retrospective analysis of the attributes of both invasive and non-invasive woody plant species to develop statistical models and a decision tree for evaluating invasive potential of new introductions. Such information could be used in the development of an introduction policy as described above.

Methods

Selection of Species

We analyzed the traits of woody plant species known to have been introduced into North America north of the United States/Mexico border prior to 1930. These species were judged to have ample time to become invasive if they had that potential. We divided the species into two groups: invasive species (verified to maintain self-sustaining populations outside cultivation) and non-invasive (not documented outside cultivation). We identified the invasive species first by using the U. S. Department of Agriculture's *National List of Scientific Plant Names* (1982), which lists species known to occur in the country, then verified their invasive status by checking herbarium collections and by contacting resource managers and others around the country. This research identified 235 species (list available from the corresponding author), 76 of which were considered by resource managers and other sources to be of particular concern and we designated these as "pest species" for some analyses. We judged a species non-invasive if it was listed in nursery and seed catalogs from early in the century, but had not been found outside of cultivation. A total of 114 species met that criterion. Other species may have been introduced prior to 1930 but because many were listed only by common name we could not identify them to species. The invaders in our sample represented 53 families and 125 genera, and the non-invaders were from 48 families and 80 genera. This broad representation provides sufficient phylogenetic diversity to allow us to detect and correct for correlations due more to common ancestry than to invasive ability.

Attributes and Data Analysis

We selected traits that are a priori likely to influence invasiveness directly or indirectly and that can be determined from the literature or herbarium specimens (Table 1). Most of those we analyzed have been suggested by various authors, including Baker (1965, 1974) and Roy (1990). One hundred and seventy-five sources were consulted to get information about each attribute for each species (Reichard 1994).

We used discriminant analysis (DA) to find linear combinations of attributes that maximized the variation between the two groups while minimizing the variation within each group (Norusis 1993). The stepwise selection procedure within SPSS for Windows (Release 6.0, 1993) selected and removed the variables with the highest discriminating power, then reevaluated the data before removing the next variable. Those attributes that, when combined with others, provided the best discriminating power were used to create the models. At each step the variable resulting in the smallest Wilks' lambda was selected by the procedure. We fit the models using a random selection of approximately 75% of the species and then tested the model on the remaining portion. Species that were missing variables for one of the attributes were omitted, reducing the total number of species used for that model. We repeated the process for a data set that included only angiosperms introduced into temperate North America (i.e., conifers and southern Florida species were omitted because the attributes unique to these two groups sometimes obscured the patterns present in the remainder of the species).

We also generated Classification and Regression Trees (CART) to test whether it was possible to predict invasiveness based on the attributes we analyzed (Brieman et al. 1984). The goal of CART is to predict what class a species is in, using an analysis of the structure of the data on that species. Unlike stepwise discriminant analysis no assumptions about normality are made and continuous measurements and categorical data are appropriately used (Brieman et al. 1984). Unlike DA, CART does not search for a linear combination of attributes, but instead breaks down the data set attribute by attribute to develop a dichotomously branching "tree" for decision-making (Brieman et al. 1984). The results are presented in a hierarchical binary tree classification that is easily translated into a simple method of predicting invasiveness. We treated missing values for attributes as we did for the discriminant analysis. We split the data randomly into 10 groups and fit a model to one of the groups, and then passed the remaining groups through the model to calculate a misclassification rate. These steps were repeated until a model had been fit to each group and tested on the rest. Once a tree was established, the lowest branch pair was "pruned" and the misclassification rate was recalculated. Successive branches were pruned until the lowest cross-validation misclassification rate was found on a simplified tree and that was considered the "best" tree. The procedure was performed on both the full species data set and angiosperms introduced into temperate North America, with the same attributes used in creating the DA models.

Table 1. Plant characteristics used to create the discriminant analysis and classification and regression tree models.

Character	*Character state*
Native range	North America, Eurasia, Great Britain/North Europe, Mediterranean, Australia/New Zealand, temperate Asia, tropical Asia, tropical America, temperate South America, Africa, interspecific hybrid
Invades elsewhere	yes/no
Leaf longevity	evergreen, deciduous, semi-evergreen
Polyploidy	yes/no
Reproductive system	perfect, monoecious, dioecious
Vegetative reproduction	yes/no
Minimum juvenile period	years
Length of the flowering period	months
Flowering season	all year, winter, early spring, late spring, summer, fall
Length of the fruiting period	months
Fruiting season	all year, fall, fall and winter, winter, spring, summer
Dispersal mechanism	biotic/abiotic
Seed size	millimeter
Seed germination requirements	none, cold, chilling, scarification, cold chilling and scarification

We combined the results of these methods of analysis, as well as differences between invaders and non-invaders, for these attributes and taxonomic relationships (Reichard 1994) to create a decision tree that evaluates invasive potential using traits to create several different predictive paths. Several versions were tested using the attributes found to be important in the analyses and using the total species available. The version with the lowest misclassification rate was selected. Rather than identify the species simply as invasive or not invasive, this predictive model has three categories: "admit" (low probability of invasiveness), "do not admit" (very high probability of invasiveness), and "further analysis needed" (intermediate probability of invasiveness). The latter category acknowledges that some species cannot be easily distinguished because the risk of establishment cannot be sufficiently determined without examination of additional characteristics. It would require that the species be denied admission until additional information was considered. The decision tree uses only a portion of the attributes used in the discriminant analysis and further analyses of the unused attributes, such as the length of flowering and fruiting times and other attributes associated with invasiveness, such as self-compatibility and agamospermy (Reichard 1994) could be more decisive. Extensive post-introduction monitoring would also be a required component.

Results

Discriminant Analysis

Some of the attributes positively or negatively associated with invasiveness were related to taxonomic or geographic factors (Table 2). Evergreen leaves were associated with non-invasiveness primarily because of conifers, all of which were evergreen and which account for only 1% of invasive species in North America, but 14% of the non-invaders. Evergreenness, however, was still associated with non-invasiveness when conifers and all southern Florida species were deleted from the analysis (Table 2). Perfect flowers were associated with invasiveness, but this is strongly influenced by the lack of conifers (all of which have unisexual reproductive structures) in the invasive group for North America and their presence in the non-invasive group. When only angiosperms are considered there are no differences in reproductive systems.

Geographic origin of the species provided some predictive clues. Species native to regions of North America other than the regions in which they were offered for sale were unlikely to invade, as were interspecific hybrids of nursery origin (which are generally sterile). Some of the results related to geographic origin are very misleading, however. The continent-wide model associated species native to temperate Asia with a lack of invasiveness, but in some regions (e.g., the southeastern United States) large numbers of the invasive species are from temperate Asia. Although geographic origin was selected statistically for use in these larger-scale models, it may be most useful in regional models.

The knowledge that a species has invaded elsewhere in the world strongly contributed to the identification of invasive species. When "elsewhere" is omitted as a possible trait in analyses, however, an accurate predictive model is still possible (Table 2). The ability to reproduce vegetatively, a trait used as a basis for predicting invasions in Australia (Panetta 1993), was positively associated with invasiveness. The lack of pre-germination

Table 2. Predictive models created using discriminant analysis of the North American invasive species data set.*

Variables contributing to discriminant analysis model	*Function coefficients*		
	All species	*Temperate angiosperms*	*Excluding "invades elsewhere"*
Leaves evergreen	0.41367	0.46754	0.63676
Invades elsewhere	−0.34944	−0.39920	N/A
Vegetative reproduction	−0.30118	−0.47791	−0.34800
Flowers perfect	−0.23794		
Flowers in winter	0.25996		
Length of time fruit is on plant	−0.28076		−0.44657
No seed pretreatment			−0.33202
Cold needed for seed germination	0.32293		
Native to temperate Asia	0.34193		0.32999
Native to N. America (other areas)	0.69956	0.72227	0.91021
Intraspecific hybrid	0.52100	0.59979	0.51708
Canonical correlation	0.667	0.582	0.628
Wilks' lambda	0.555	0.661	0.605

**Blank spaces indicate that the character was not selected as a discriminating variable. Positive values are associated with non-invasive species, negative with invasive.*

Table 3. Validation of the discriminant analysis models (Table 2).

Actual group	No. of species	Predicted group membership (%) Invader	Non-invader	Overall classification (%)
All species				
invader	34	33 (97.1)	1 (2.9)	86.2
non-invader	24	7 (29.2)	17 (70.8)	
Temperate angiosperms				
invader	48	45 (93.8)	3 (6.3)	81.7
non-invader	23	10 (43.5)	13 (56.5)	
Excluding "invades elsewhere" attribute				
invader	33	29 (87.9)	4 (12.2)	76.5
non-invader	18	8 (44.4)	10 (55.6)	

treatment requirements for the seeds was also correlated with invasiveness, a finding consistent with Baker's idea that a weedy species would have germination requirements met under many environmental conditions (Baker 1974). A long fruiting period, evergreen leaves, a native range in temperate Asia or other parts of North America, and origin by interspecific hybridization were positively associated with the non-invasiveness.

The discriminant analysis model using the full data set was created using 149 species (72%) and tested on the remaining 58 species (28%). The Wilks' lambda was fairly large (0.555), suggesting high variance within the groups, but the canonical correlation was 0.667, indicating that 67% of the variance was explained by the selected variables. It correctly classified 86.2% of the species in cross-validation (Table 3). The rate for correctly classifying invaders was very high (97.1%). Only one species, *Celastrus orbiculatus*, an aggressive pest of wooded areas, wetlands, and riparian zones in the east and midwest was misclassified. It was misclassified because, although it fits half the characteristics in the model of an invasive species, it is not known to invade elsewhere in the world, is dioecious, and is native to temperate Asia, all characteristics of a non-invasive species in this model. The model correctly classified only 70.8% of the non-invasive species; this asymmetry in predictive power characterizes all the DA models generated.

A discriminant analysis model (Table 2) created using only temperate angiosperm species did not retain five attributes found in the full North American model. Of these attributes one, perfect flowers, was included in the North American model largely because of the influence of conifers (which are monoecious or dioecious) in that data set. The other four, flowering in winter, long fruiting period, cold chilling for seed germination, and origin in temperate Asia, are all attributes that, although important in many regions in North America, are strongly influenced by the inclusion of Florida species (Reichard 1994), either because they were strongly associated with the species (the first two attributes) or strongly disassociated (the latter two). The model for temperate angiosperms therefore eliminated some regional and phylogenetic bias found in the full North American model. It retained the other attributes from the full North American model. The model was created using 169 species (70%) and tested on the remaining 71 (28%). It was comparable in accuracy, with 81.7% of the species correctly predicted (Table 3). Forty-five of the 48 (93.8%) invasive species, but only 56.5% of the non-invasive, were correctly identified (Table 3). The Wilks' lambda was high (0.661) and the canonical correlation for the function indicates that only 58% of the variance was explained by the attributes selected, perhaps resulting in the poor predictive power for the non-invasive species.

The model that excluded the "invades elsewhere" trait used the same attributes as the complete model with the exception of perfect flowers, flowers in winter, and cold needed for seed germination (Table 3). It was created using 233 species (82%) and validated on the remaining 51 species (18%). It also had high predictive ability for invasive success based mostly on plant attributes. It successfully identified 87.9% of the invaders, but only 55.6% of the non-invaders, a rate one would expect from chance alone (Table 3). The overall rate was 76.5%. It had a fairly high Wilks' lambda (0.605), indicating high variance, but the attributes used accounted for 63% of the variance.

Classification and Regression Trees

The pruned tree generated by CART contained only four variables (Fig. 1), all of which were also in the DA model for the full data set. Unlike the DA model, the CART model was more accurate in predicting non-invasiveness than invasiveness, separating them using only three attributes: native to North America, interspecific hybrids, and the failure to invade elsewhere in the world. Invasive species, on the other hand, are largely identified by vegetative reproduction and invading elsewhere. The full, unpruned model was 90.0% accurate in its predictions (Table 4) but, because it used all the attributes en-

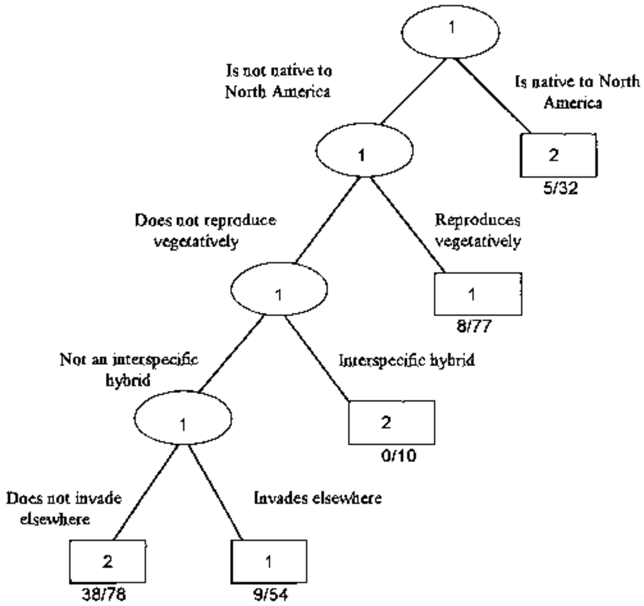

Figure 1. Pruned classification and regression tree for predicting invasive potential in introduced woody plants in North America. Terminal nodes (where group determination is made) are square boxes. Group 1 species are invasive, group 2 are non-invasive. The number to the right of the slash under each box is the number of species classified by the path leading to the box. The number to the left is the number of those that are misclassified (e.g., in results of the first split, 5 of the 32 species identified as in group 2 are actually in group 1).

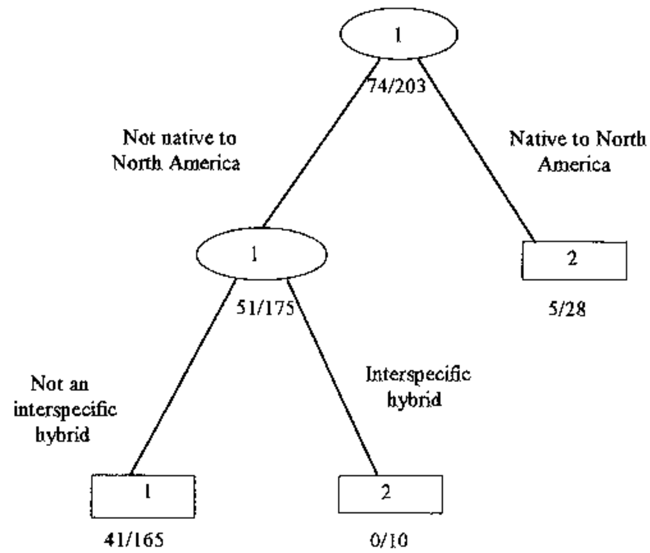

Figure 2. Pruned classification and regression tree for predicting invasive potential in introduced temperate angiosperms in North America. Terminal nodes (where group determination is indicated) are square boxes. Group 1 species are invasive, group 2 are non-invasive. The number to the right of the slash under each box is the number of species classified by the path leading to the box. The number to the left is the number of those that are misclassified.

tered, it was more difficult to use. A pruned CART model created using only temperate angiosperms in the data set (Fig. 2) was 96% accurate in predicting invasiveness in cross-validation using only two attributes: origin outside of North America or not an interspecific hybrid (Table 4). These attributes, although adequate for identifying invaders, failed to identify the non-invasive species; 45.0% correctly predicted is somewhat less than the 50.0% one would expect by chance. The largest portion of the misclassification is the result of the left arm of the model (Fig. 2), where all non-invasive species are classified as either North American or interspecific in origin, an oversimplification.

Decision tree

The decision tree (Fig. 3) used elements found to be important in the previous analyses as well as attribute comparisons (Reichard 1994). It also uses knowledge about the relationship of the species to families and genera that are already pests in North America. Of the 76 pest species studied 63% were in six families: Rosaceae, Fabaceae (*sensu lato*), Myrtacae, Salicaceae, Oleaceae, and Caprifoliaceae (*sensu lato*). Just as knowledge that a species invades elsewhere indicates that it has invasive tendencies, knowledge that a species is related to one already in-

Table 4. Validation of the classification and regression trees (Figs. 1 and 2).

Actual group	*No. of species*	*Predicted group membership (%)*		*Overall classification (%)*
		Invader	*Non-invader*	
All species				
invader	157	114 (73.0)	43 (27.0)	76.0
non-invader	94	17 (18.0)	77 (82.0)	
Temperate angiosperms				
invader	134	129 (96.0)	5 (4.0)	77.3
non-invader	74	41 (55.0)	33 (45.0)	

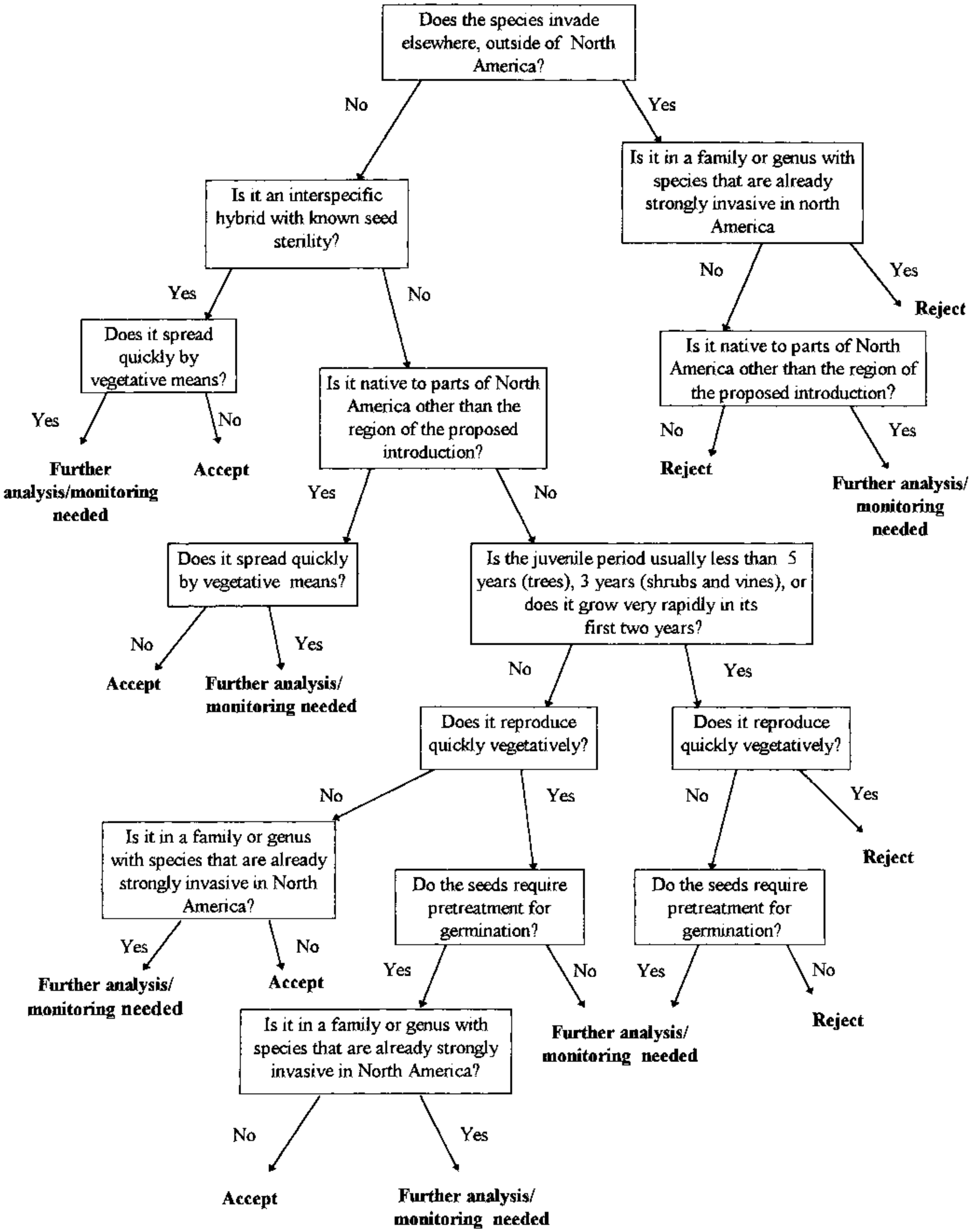

Figure 3. Decision tree for woody North America invasive species. Acceptance status refers to the decisions regarding possible introduction of the species.

Table 5. Validation of the decision tree (Fig. 3).*

Actual group	*No. of species*	*Admission status* Accept	Reject admission	Further analysis
Invaders	204	3 (2%)	174 85.0%	27 13.0%
"Pest" invaders	76	0	67 88.0%	9 12.0%
Non-invaders	87	40 46.0%	16 18.0%	31 36.0%

**Validation is based on a testing of all invasive and non-invasive species and those considered to be pests by various experts.*

vading may indicate that they share traits related to invasive success through descent from a common ancestor.

Like the discriminant analysis and regression trees, the decision tree also had high predictive value. Only three invasive species (*Picea abies*, *Betula pendula*, and *Poncirus trifoliata*), all minor invaders, were recommended for acceptance into North America (Table 5). No pest species were accepted. One hundred and seventy-four species, or 85.0% of those evaluated, were rejected outright, including 88.0% of the 76 pest species. One-hundred and twenty-seven species were rejected for admission on the strength of their invading elsewhere, belonging to an already invasive taxonomic group, and not being native to other parts of North America. Even when that arm of the tree was excluded, however, only eight (7%) of the invasive species and only one pest species (*Ilex aquifolium*) were admitted unconditionally following the other paths in the chart, indicating that the tree may be effective even when information on invasiveness elsewhere is unavailable (although 89 species could not be re-evaluated due to missing information about a pertinent attribute). In the validation, 13.0% of the species were recommended for further analysis and monitoring (see below) before a recommendation for admission or denial could be made. This could include conditional admission with extensive monitoring.

As in the DA, the rate of accurate prediction was lower for the non-invasive species, 46.0% of which were admitted, 18.0% were rejected, and 36.0% were recommended for further analysis. All but three of the species were denied admission on the basis of invading elsewhere and being in a previously invasive taxonomic group. Because of the strong correlation between invading elsewhere with invading in North America, it is prudent to exclude species not currently invasive if they score positively for that attribute, especially if they are related to current invaders. They may be considered incipient invaders. Although carrying out further analyses would be an additional burden, the conservative approach would likely prevent many potentially invasive species from becoming introduced.

Discussion

Biological invasions are an international problem and various methods for predicting invasive status have been proposed. Some have been qualitative, but systematic (e.g., Panetta 1993). Some have used statistical approaches similar to those discussed here. For instance, annual species in Great Britain were categorized by weediness and subjected to a number of analyses; only comparisons of congeners provided predictive ability by length of flowering time (Perrins et al. 1992). Scott and Panetta (1993) used multiple regression to predict the weed status of southern African species introduced into Australia, finding that taxonomic and geographic variables associated with the species predicted agricultural weeds, but no variables predicted environmental weeds. Rejmánek and Richardson (1996), used discriminant analysis on pine species, finding that invasive pines can be accurately detected from non-invasive based on the minimum juvenile period, mean seed mass, and mean interval between seed crops. Other attempts such as Richardson et al. (1990) and Tucker and Richardson (1995) have utilized the characteristics of invaded ecosystems and the biological attributes of invaders to predict which species will invade. This method appears to be especially effective in systems that experience episodic disturbance. The disturbance removes barriers to invasion and successful invaders then invade in the following invasion window. The problem of invasions and the attempts to predict them are worldwide even though particular screening protocols and their acceptance may be influenced by the cultural history of nations.

Even the best analytical method cannot yield totally accurate predictions, because of environmental stochasticity and/or an inevitable incompleteness in attributes evaluated. Nonetheless, in the preceding analyses, we were able to predict invasive potential for plants introduced in North America with a level of accuracy far better than expected by chance. Using simple attributes available through published sources and on herbarium specimens, we attained overall predictive rates of 76.5% (CART) to 86.2% (DA). The single-most reliable predictor in the models was whether or not a species was known to invade elsewhere in the world, an attribute that is also a key component of a screening system proposed for Australia (Panetta 1993). More than half of the invasive species had invaded elsewhere, whereas only 15% of the non-invasive species had done so. While this was the best discriminating variable, even when it was omitted we obtained predictive rates of 76.0% overall using DA. Thus, biological and geographic attributes can be used to evaluate invasive potential in the absence of previously demonstrated invasive behavior.

That so many species invade repeatedly lends credence to the idea that, whereas interactions with the environment may affect invasiveness, the characteristics of the species themselves dominate invasive ability. The ability of a species to invade repeatedly is likely related to reproductive attributes, although of those studied, only increased flowering and fruiting were correlated with the "elsewhere" attribute. Increased flowering time was associated with weedy annuals in Great Britain in a comparison of invasive and non-invasive congeners (Perrins et al. 1992). It is also probable that still other attributes, perhaps physiological, are contributing to the ubiquitous success of the "elsewhere" invaders. The importance of this attribute also lends strong support to the need for a global database of invasive species such as has been proposed by the Survival Species Commission of the World Conservation Union (Clout 1994) and by the Adaptive Research Programme of the University of Oxford (see Worldwide Web site <http://ifs.plants.ox.ac.uk/wwd/wwd.html> for more information on the progress of the latter database).

The greatest difficulty in the DA models (and in the decision tree) was not in predicting which species would invade, but which would not. Consistently the highest proportion of misclassification was in that category. Non-invaders appear to be best described in the CART model using all species, which identify them as not invading elsewhere, being native to North America, and being an interspecific hybrid. Further research into consistent non-invaders should both increase fairness of a predictive introduction scheme to the nursery industry and perhaps shed greater light on the biology of invaders as well.

The decision tree, developed from the DA and CART models, as well as attribute comparisons (Reichard 1994), provides an easy and highly accurate evaluative technique using several different attribute paths. Because there are many strategies that would potentially lead to a successful invasion, no single set of attributes is expected to define an invader. The outcomes correspond to policy decisions that must be made: acceptance, denial of a species proposed for introduction, or delaying introduction until further analysis/monitoring is completed. The decision tree is flexible and would permit continued importation of non-native species, two premises fundamental to a screening system (Waterworth & White 1982). It makes use of our growing understanding of the biology of invaders, puts the burden of proof on the group most likely to benefit from the introduction, and could do a better job of protecting our natural resources than does current policy. Introduction of new agricultural and horticultural species could be shifted to superior cultivars of North American natives, a shift that reflects current trends in water conservation and management (Sauer 1995), and to the development of sterile interspecific hybrids. The latter should be considered with some caution; seemingly sterile interspecific hybrids can, through later chromosome doubling, become fertile (Marchant 1968). Sterile hybrids that are capable of vigorous vegetative reproduction also should be avoided.

The information about the species needed to complete the evaluation using the decision tree is generally not difficult to find. Computerized abstract searches using services such as AGRICOLA often reveal a number of articles about reproductive biology. Even seemingly obscure species have often been evaluated by government and non-government organizations for economic value and reproductive characters are discussed in the organizations' research and technical papers. Germination requirements may be quickly and easily determined experimentally. In evaluating the species using the decision tree the trait most commonly unknown was the minimum juvenile period. Correlations between rapid vegetative growth and the early attainment of reproductive capabilities may allow estimates to be made.

Several other attributes should be investigated further. First, although many invasive plants have a wide ecological amplitude, there does appear to be a correspondence between the climate of a species' native range and its ability to invade a particular region once introduced to it (Baker 1974; Kruger et al. 1986; Panetta & Mitchell 1991). Close examination of minimum and maximum temperatures and average precipitation in a species' native range may be helpful. The latitude range of the species may indicate the adaptability of the species to varying conditions and was suggested by Daehler and Strong (1993) to have high predictive value and some studies seem to have verified this (Scott & Panetta 1993; Reichard 1994; Rejmánek 1995). In addition, species should be studied for self-compatibility and agamospermy, attributes that differed significantly between invasive and non-invasive species in analysis (Reichard 1994). The average number of seeds per plant produced in a growing season and the species' dispersal mode should be documented. Finally, the length of the flowering and fruiting periods differ between invaders and non-invaders (Reichard 1994) and may provide useful evaluative information. Data on physiological factors, such as tolerance of xeric conditions, should also be gathered because they may prove to have predictive power.

The models and decision tree presented here, as well as most other such systems developed (e.g., Perrins et al. 1992; Panetta 1993; Scott & Panetta 1993; Tucker & Richardson 1995; Rejmánek & Richardson 1996), predict only the potential of a species to disperse from introduced plants, it does not attempt to predict impact. Predicting the impact of a species after establishment is a much more difficult task. Increasing information about the affect of particular non-native species on particular native communities and organisms may allow predictions of impact to be made in the future.

Caution should be advised in applying the results of these predictive analyses to other taxonomic groups, including annual plant species. For instance, vegetative reproduction, important in our analyses, is rare among annual plants, although it may be found in herbaceous perennials. The methods presented here, but not the specific details, may be useful for other taxonomic groups.

Conclusion

In the last 200 years as intercontinental travel has increased we have effectively broken down barriers to plant dispersal that have driven evolution since the breakup of Pangaea, the original supercontinent. Without a thought to the dynamics that we were setting in motion we introduced species to places they, or even similar species, have never existed. That thoughtlessness has led to serious consequences as the introduced species have competed with natives and altered ecosystem processes. It is time to move from reaction to our previous thoughtlessness to the thoughtful prevention of harmful species. To do this we must develop predictive methods that allow us to distinguish harmful from innocuous species.

The models described in this paper, as well as other predictive methods recently developed (Panetta 1993; Scott & Panetta 1993; Tucker & Richardson 1995; Rejmánek & Richardson 1996) demonstrate that it is possible to predict invasive success based on plant traits and what is known about the range, both native and introduced, of the species. The decision tree shows that a predictive method can be accessible, straightforward, and accurate. Such models and decision guides are the first step toward developing policy that is restrictive but fair to those requiring the introduction of species. We do not have to be resigned to a flood of invading species, nor do we have to deny agriculturists and horticulturists the opportunity to provide their customers with new plants. Industry could be allowed to import new species if the potential for invasiveness were evaluated before importation is allowed. The economic value of the species *must* be secondary to the assessment of invasive potential; if a species is judged to have high invasive potential, rejection for introduction is the prudent policy. Protocols should and can be developed and accepted by the U. S. Department of Agriculture that would screen plants proposed for introduction for any purpose for invasive potential and for impact on native species and ecosystems.

We offer the following recommendations regarding the development of protocols for the introduction of woody species:

(1) Do not intentionally allow species that have a demonstrated capacity to be injurious to native organisms and/or systems in other parts of the world into the country. The probability of invasiveness has been shown to be high.

(2) Use a hierarchical tiered approach to evaluating the species, such as the one provided by the decision model. Some species appear to have low invasive potential (e.g., hybrids that do not vegetatively reproduce) and their entry could be expedited. Others may require more extensive, and thus more costly, analysis and monitoring.

(3) Research into species that consistently have failed to invade should be pursued to increase the number of species appropriate for introduction and to further knowledge of the biology of invasiveness.

We suggest that the costs of screening plants for invasive potential be born by those that would profit by them: the importers. The importers, in exchange, could be given an economic incentive to comply with the screening process. If a species is screened and judged to have a low probability of invasive potential, the importer would have exclusive control and distribution rights for all cultivars of that species for a specified period of time. More detailed analyses, if needed, could result in a longer "patent" period. The patent would not be a seal of approval by the federal government, but an acknowledgment of the importer's investment and compliance with regulations. If the species became invasive despite following procedures and protocols the importer should not be held responsible. To do so would only encourage circumvention of the process. A reserve fund for control of those species that do invade could come from a portion of the fees charged for evaluation.

Finally, we suggest that those aware of the problems caused by invasive plants should continue to educate the importers of non-native plants, as well as the buying public, to the potential environmental risks associated with unmanaged importation. Increasing awareness will encourage voluntary compliance with screening protocols, which is the easiest and least expensive way to ensure that native ecosystems are protected from invasive species.

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