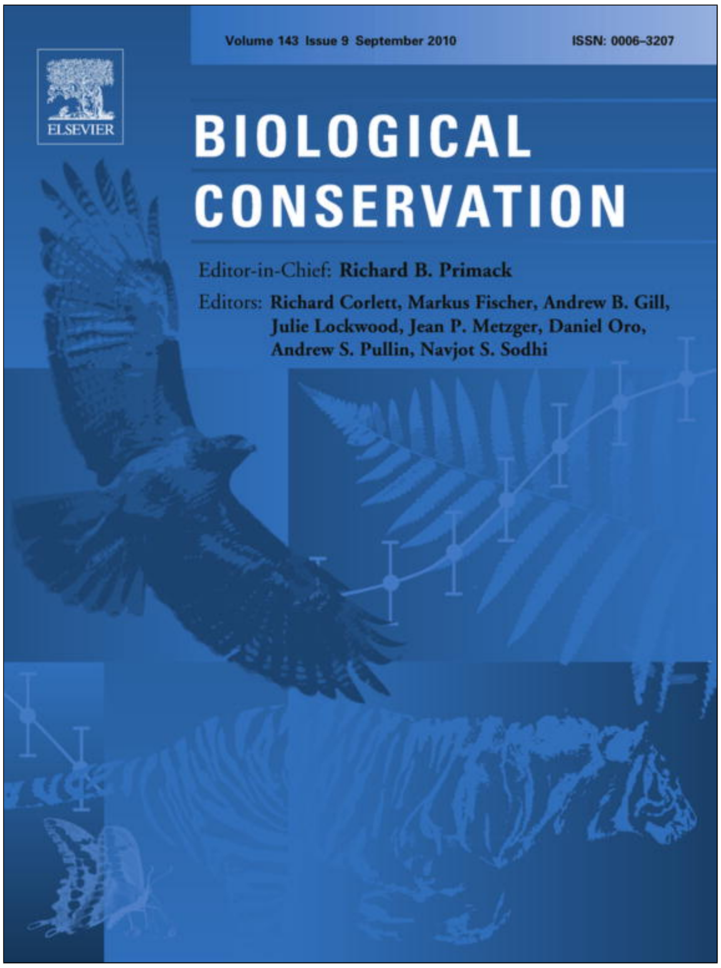
Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

Biological Conservation 143 (2010) 2070–2079

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Risk assessment: Simultaneously prioritizing the control of invasive plant species and the conservation of rare plant species

Thaddeus K. Miller [a,*], Craig R. Allen [a], Wayne G. Landis [b], James W. Merchant [c]

[a] Nebraska Cooperative Fish and Wildlife Research Unit, University of Nebraska – Lincoln, 422 Hardin Hall, 3310 Holdrege Street Lincoln, NE 68583-0984, United States
[b] Institute of Environmental Toxicology, Huxley College of the Environment, Western Washington University, 516 High Street, Bellingham, WA 98225-9180, United States
[c] Center for Advanced Land Management Information Technologies, University of Nebraska – Lincoln, 306 Hardin Hall, 3310 Holdrege Street Lincoln, NE 68583-0973, United States

A R T I C L E   I N F O

Article history:
Received 30 October 2009
Received in revised form 22 April 2010
Accepted 23 May 2010
Available online 16 June 2010

Keywords:
Relative Risk Model
Rare
Endangered
Invasive
Non-indigenous
Plants

A B S T R A C T

Although the consequences of the homogenization of Earth's flora and fauna are not well understood, experts agree that biological invasions pose hazards to rare species. As a result, there is a need for a systematic approach to assess risks from invasive species. The Relative Risk Model can be adapted to assess combinations of rare species, invasive species, and regions. It also can be applied to different taxonomic groups and at different spatial scales. This flexibility makes it a promising tool for invasive species risk assessment. We used the Relative Risk Model to quantify risks posed to endangered plant species by non-indigenous invasive plant species in Nebraska.

We modeled the suitable habitats for eight invasive plant species, which we subsequently compared to documented occurrences of endangered plant species in a Geographic Information System. We combined this data with an assessment of the ecological impacts of each invasive species in a regional risk assessment framework to simultaneously calculate relative risk scores for invasive plant species, imperiled plant species, and subregions. We assessed uncertainty with Monte Carlo simulations.

The results of this assessment are discrete values indicating the relative threat posed by invasive species to rare species, the relative risk posed to the rare species, and the relative risk in subregions. Results indicate that the invasive species *Elaeagnus angustifolia* and *Rhamnus cathartica* pose the greatest risks to endangered plants in Nebraska. The rare species *Panax quinquefolius* and the subregion Western Corn Belt Plains show the highest risk scores.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Biological invasions are one of the most significant environmental issues of the 21st century. Increases in commerce and transportation have resulted in a concomitant increase in the rate at which non-indigenous invasive species (NIS) are transported into new habitats (Elton, 1958; di Castri, 1989; Office of Technology Assessment, 1993; Ruiz et al., 2000; National Research Council, 2002). Because NIS are known to have significant negative consequences for both human enterprise and ecological systems (Pimentel et al., 2000), there is a pressing need to understand and mitigate the impacts of biological invasions.

Risk assessment presents a framework that can be used to understand and characterize the consequences of biological invasions. The Environmental Protection Agency (EPA) describes risk assessment as an evaluation of the probability of adverse ecological consequences resulting from one or more sources (United States Environmental Protection Agency, 1998). The EPA risk assessment protocol includes three steps: (1) problem formulation, (2) risk analysis, and (3) risk characterization, which present a framework that allows decision makers to compare risks from a variety of events or circumstances.

Early risk assessments were performed to evaluate the risks posed to human health, however, as the information required for other applications of risk assessment has become available, additional applications are now plausible. Numerous researchers (e.g. Bartell and Nair, 2004; Anderson et al., 2004) recommend expanding the application of risk assessment to fields such as the study of NIS. Many current efforts to characterize risks of NIS focus on evaluating the likelihood and consequences of future introductions. These efforts include the Weed Risk Assessment of Australia (Pheloung et al., 1999), the protocol designed by the National Research Council to assess non-indigenous plants in the US (National Research Council, 2002), the quantitative approach presented by Kolar and Lodge (2002), and the Weed Risk Assessment protocol used by Dawson et al. (2009). Although there are clear advantages of doing so (Keller et al., 2007), few risk assessment protocols are designed to compare the risks posed by incipient and current invasions.

* Corresponding author. Address: 3515 Apple St. Lincoln, NE 68503, United States. Tel.: +1 316 772 3604.
E-mail address: tkm8i@yahoo.com (T.K. Miller).

0006-3207/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biocon.2010.05.015

Author's personal copy

Landis (2004) developed a conceptual framework for ecological risk assessment of NIS which has been applied to evaluate risks posed by the non-indigenous invasive European green crab (*Carcinus maenas*) at Cherry Point, WA (Colnar and Landis 2007). Allen et al. (2006) performed a spatial risk assessment of the invasion of fire ants (*Solenopsis invicta*) to two native birds in South Carolina. These single-species studies demonstrate how an invader's geographic range, its abundance, and its effect on ecosystems can be combined to characterize risks from an invasive species.

The Relative Risk Model for ecological risk assessment of NIS, which was developed and applied by Landis (2004) and Colnar and Landis (2007) allows information on current extent, spread, ecological impact, and risks posed to rare species to be quantitatively compared and analyzed. The results of the Relative Risk Model are quantitative values indicating the summation of categorically ranked input variables.

Here, we use the Relative Risk Model to assess the risks of multiple invasive plant species to multiple rare plant species in subregions of Nebraska. Customary terminology used in the Relative Risk Model would refer to non-indigenous invasive species as "stressors" and rare species as "endpoints" (refer to the glossary). We demonstrate how geographical data in a Geographic Information System (GIS) can be used to characterize the likelihood that invasive species will threaten rare species. In addition, we use life history characteristics of invasive plants to characterize the ecological consequences of their invasion. We present relative risk scores for eight invasive plant species, ten rare and endangered plant species, and six ecoregions (level III ecoregions, Omernik, 1987) in Nebraska. Finally, we completed a thorough uncertainty analysis, using Monte Carlo simulation, to examine uncertainty in the data.

2. Materials and methods

Relative risk scores represent the summation of four variables, which reflect (1) the extent of an invasive species in an ecoregion, (2) the extent of habitat types that are suitable for invasion in an ecoregion, (3) the consequences of an invasive species in habitat types in an ecoregion, and (4) the degree to which rare and endangered species occur in habitat types and ecoregions that may be colonized by invasive species (Landis, 2004; Fig. 1).

2.1. Study area

The state of Nebraska is located in the central United States of America, from approximately 40 to 43°N, and 95 to 104°W. The habitats of Nebraska are dominated by grasslands, including tallgrass, shortgrass, and sandhills prairies, with oak woodlands in the east and evergreen forests in the far northwest. Nebraska also has a significant portion of land under continuous irrigated and non-irrigated cultivation. Primary agricultural crops include corn, soybeans, wheat, sugar beets, hay and alfalfa. Most of the remaining grasslands in Nebraska are used to graze cattle or are held in permanent conservation.

We used the level III ecoregion designations of Omernik (1987) to divide the state into six ecological risk regions. Ecoregions are geographic designations that reflect a combination of characteristics, including climate, geology, hydrology, land use, physiography, soils, vegetation, and wildlife (Chapman et al., 2001). Ecoregions of Nebraska include the Western High Plains, Central Great Plains, Northwestern Glaciated Plains, Northwestern Great Plains, Nebraska Sand Hills, and Western Corn Belt Plains.

2.2. Invasive species selection

We selected eight non-indigenous invasive plants from the seventeen plants listed on the Nebraska Weed Control Association "watch list" (C. Helzer, personal communication, March 15, 2007). The watch list is assembled by state weed managers based on a consensus regarding which introduced plant species could pose the greatest threats in the state. Using the NatureServe Invasive Species Assessment Protocol (Morse et al., 2004) as a coarse filter, we selected the eight species that have been evaluated and have an Invasive Species Impact Rank (called the I-rank) of "high" or "high/medium" (Table 1). An I-rank of "high" means that the species "is a severe threat to native species and ecological communities" (Morse et al., 2004). An I-rank of "high/medium" is a mixed result, which is rounded up and referred to as the rounded I-rank.

2.3. Source ranks

Source ranks indicate the magnitude of occurrence of each non-indigenous invasive species in each subregion. We used county-level data (Kaul et al., 2006) of occurrence records for invasive plants to determine the extent to which each invasive plant occurs in each ecoregion. We determined these values, which are called source ranks ($Source_{ij}$), for each invasive plant in ecoregions by $Source_{ij} = ua_{ij}/u_{ij}$, where ua_{ij} = uninfested counties adjacent to an infested county, u_{ij} = uninfested counties $\sum u = 0$; i is an ecoregion and j is an invasive plant species; if $u_{ij} = 0$ then $Source_{ij} = 1$.

The results of this metric are close to 1 under two circumstances: first, if most counties in an ecoregion have documented occurrences of the invasive plant, or second, if most counties in

Table 1
Invasive plants (stressors) included in the risk assessment.

Sources (invasive species)
Alliaria petiolata (garlic mustard)
Coronilla varia (crown vetch)
Elaeagnus angustifolia (Russian olive)
Elaeagnus umbellata (autumn olive)
Hypericum perforatum (St. Johnswort)
Lonicera maackii (Amur honeysuckle)
Phragmites australis (common reed)
Rhamnus cathartica (European buckthorn)

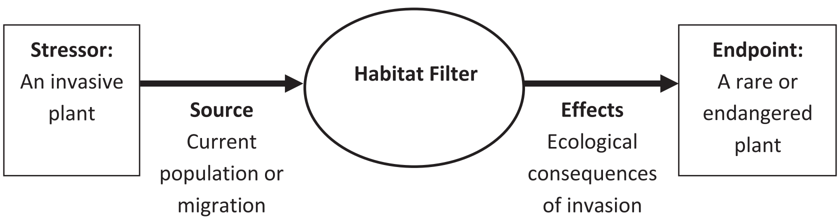


Fig. 1. Conceptual model for a risk assessment of non-indigenous invasive species impacts on rare or endangered species. Adapted from Landis (2004) and Colnar and Landis (2007).

Author's personal copy

an ecoregion are adjacent to counties with documented occurrences. This method affords an advantage over occurrence records in that it accounts for proximity of counties without confirmed records of invasive species to counties with confirmed records of the same species. For example, a county that lacks confirmed records of an invasive species could still have elevated risk, which would correspond with the number of adjacent counties that have positive records of the invasive species. In circumstances in which an invasive plant occurs in all counties in an ecoregion, it receives a value of 1.

We converted the results of the metric into categorical values reflecting absent (0), low (>0 to 1/3), medium (>1/3 to 2/3), and high (>2/3 to 1). Source ranks were represented with the values 0, 2, 4, and 6, which correspond to the categories absent, low, medium, and high respectively. The values 0, 2, 4, and 6 were chosen partly for tradition, and partly to scale the results in a manner that is easily interpreted (similar to Hart Hayes and Landis (2004)). Because of how risk scores are calculated, the absolute values associated with each category only affect the magnitude of the scale of output values.

2.4. Habitat ranks

We created maps of 17 land cover categories, derived from the 2001 USGS land cover dataset (United States Geographical Survey, 2007), National Wetlands Inventory data (Cowardin et al., 1979, United States Fish and Wildlife Service, 2007a,b), and Soil Survey Geographic Database (SSURGO) data (Natural Resources Conservation Service, 2006, 2007a,b), which reflect habitat types in Nebraska (Table 2). The abundance of each habitat type in each ecoregion corresponds with the potential for exposure – i.e., an ecoregion that includes no habitat that is either suitable for colonization by an invasive species or suitable for a rare or endangered species will have no potential exposure (Colnar and Landis, 2007). Conversely, an ecoregion that is dominated by a habitat that is both suitable for colonization by an invasive species and is home to a rare or endangered species will have high risk of exposure. Using the Jenks Natural Breaks classification algorithm in ArcGIS® we categorized ecoregion-habitat combinations based on the area of each habitat type in each ecoregion. Ranks of absent, low, medium, or high are represented in the model with the corresponding values of 0, 2, 4, and 6.

Table 2
Land cover categories that reflect habitats of Nebraska, derived from the USGS NLCD, National Wetlands Inventory (NWI) data, and Soil Survey Geographic Database (SSURGO) data.

Data source	Land cover category/habitat
USGS NLCD	Barren land
	Cultivated/hay
	Deciduous forest
	Developed land
	Emergent Herbaceous Wetlands
	Evergreen forest
	Grassland/herbaceous
	Mixed forest
	Open water
	Pasture/hay
	Shrub/scrub
	Woody wetlands
NWI	Forest/shrub wetland
	River/Lakeshore Wetlands
	Shallow waters
SSURGO	Hydric soil
	Riparian lowland

2.5. Effects filter

We used published literature (including floras, field guides, invasive species management documents, published scientific literature, and other literature) to determine which habitat types are invaded by each invasive species and to characterize the consequences of invasion by each invasive species in each habitat type. The consequences of invasion are referred to as "effects" in the risk assessment model. Based on life history characteristics, we determined whether each invasive plant species will alter resource allocation, alter recruitment of native species, alter the structure of the vegetation, or form monotypic stands that exclude other species.

Criteria for determining whether an invasive plant species results in an effect were determined with the most specific data available. We considered an invasive plant to alter resource allocation if it adds nutrients to soil (e.g., legumes) or if it is documented to alter ecosystems by changing patterns of resource use. An invasive plant will alter recruitment of native species if it has allelopathic characteristics or if it is known to competitively exclude other species. Stand structure may be altered by either creating overstory in grasslands, barrens, or herbaceous wetlands (e.g., woody species in grasslands), or by creating additional understory in a wooded community (e.g., herbaceous and woody plants in woodlands). Finally, the tendency of an invasive plant species to form monotypic stands that exclude other species was determined by review of published literature. We excluded one obvious effect – altering disturbance regimes – because literature regarding whether certain invasive plants do so was inconsistently available. Each effect is represented with either a 0 if it does not occur or a 1 if it is induced by an invasive plant in a habitat type, in an ecoregion.

2.6. Exposure filter

The exposure filter indicates whether an invasive plant will have negative consequences in a habitat type in an ecoregion in which a rare or endangered species occurs. The exposure filter incorporates spatial occurrence data for rare and endangered species. We selected 10 rare species for the state of Nebraska (Table 3). Nine of the 10 species are considered either critically imperiled or imperiled in the state and critically imperiled, imperiled, or very rare globally (Schneider et al., 2005) because of rarity. We added *Platanthera praeclara*, which was recently moved from the imperiled to rare rank at both the state and global levels (Schneider et al., 2005; NatureServe, 2007).

The Nebraska Game and Parks Commission Natural Heritage Program provided geospatial polygon data for rare species occurrence records in Nebraska (Nebraska Natural Heritage Program, 2007). Each polygon feature marks an individual or population of the rare species. The size of the polygon corresponds with the geospatial uncertainty of the record location (i.e., large polygons have high uncertainty) (Rick Schneider, personal communication, 2007).

Table 3
Rare and endangered species (endpoints) included in analysis.

Imperiled species
Botrychium campestre (Iowa moonwort)
Chenopodium cycloides (Sandhill goosefoot)
Dalea cylindriceps (Andean prairie clover)
Eleocharis wolfii (Wolf's spikerush)
Gaura neomexicana ssp. *Coloradensis* (Colorado butterfly plant)
Lomatium nuttallii (Nutall's biscuitroot)
Panax quinquefolius (American ginseng)
Penstemon haydenii (Blowout penstemon)
Platanthera praeclara (Western prairie white fringed orchid)
Spiranthes diluvialis (Ute lady's tresses)

Author's personal copy

We used the Jenks Natural Breaks algorithm in ArcGIS® to classify rare species polygons into three categories based on area. We omitted polygons in the largest two categories, which had perimeters $\geqslant 12550$ m. This reduced erroneous rare species-habitat associations and uncertainty. We also omitted those records with a "historical" attribute, which referred to records for rare species occurrences have not been verified for at least 30 years.

Exposure filter values indicate the degree to which each habitat type and each ecoregion explain the occurrence of each rare species. We found exposure filter ranks by first intersecting the spatial rare species data with the habitat datasets. We calculated ranks for rare species-habitat associations by finding the proportion for each association. As a result of using multiple spatial land cover data sets, some categories from different data sets represent similar habitats (e.g. Emergent Herbaceous Wetlands and River/Lakeshore Wetlands, from the USGS and NWI data sets respectively). In order to avoid counting these corresponding areas more than once, these categories required correction. Therefore, we normalized area values so that the total of corresponding areas summed to total that would occur if a single statewide habitat layer were used. Ranks for rare species-habitat associations are represented categorically, from absent (0.0) to high (1.0) in increments of 1/10th. Ranks are further divided between ecoregions, based on the degree to which each ecoregion explains the occurrence of each rare species.

3. Calculations

Relative risk scores for invasive plants are calculated with Eq. (1). Formulas for computing risk scores for ecoregions, habitats, and rare species are given in Appendix B. Since risk values are the sum of products, the absolute values of input variables do not matter. Only relative values are important, and they affect the magnitude of the final results. Changes in the scale of input variables affect all computed risk scores proportionally. We used the formula to find the relative contribution of individual invasive species to risk scores in habitat types as well.

$$RRS_{Stressorj} = \sum (S_{ij} \times H_{il} \times E_{ijkl} \times X_{ilm}) \quad (1)$$

Eq. (1): Adapted from Hart Hayes and Landis (2004).

RRS is the relative risk score for invasive species; S_{ij} is the source ranks in ecoregions; H_{il} is the habitat ranks in ecoregions; E_{ijkl} is the effects in ecoregions for stressor-effect-habitat combinations; X_{ilm} is the exposure filter in ecoregions for each habitat-endpoint combination; *i* is the ecoregion series (*Alliaria petiolata*...*Rhamnus cathartica*); *j* is the invasive species series (*A. petiolata*...*R. cathartica*); *k* is the effects series (resource allocation...spatial arrangement); *l* is the habitat series (barren land...Riparian lowland); *m* is the endpoint series (*Botrychium campestre*...*Spiranthes diluvialis*).

3.1. Supporting information

We included expert opinion to clarify habitat relationships for invasive species and rare species, so that effects where co-occurrence in the same habitat was unlikely were not erroneously included. This could occur because declining and invasive species differentiate suitable habitats at a finer scale than that which is resolved by the habitat maps. Two botanical experts familiar with the flora of Nebraska identified circumstances in which invasive species may have direct effects, indirect effects, or no impact on rare species. They also indicated whether the potential for a threat is unknown (personal communication, Gerry Steinaur, Steve Rolfsmeier, July 2008).

We summarized this information in the following manner: In circumstances when both experts agreed that there are either direct or indirect effects, or when one expert identified direct or indirect effects and the other stated that the effects are unknown, we concluded that there is potential for effects between the invasive species and rare species. Circumstances in which both experts agreed that there is no potential for direct or indirect effects were treated accordingly. In some cases, one expert's opinion was in conflict to that of the other. This was resolved in the uncertainty analysis.

3.2. Uncertainty analysis

Uncertainty may arise from spatial and categorical error in the habitat datasets, bias in occurrence data for stressors, omission of possible effects and sources, small sample sizes for some rare species, otherwise imperfect data, and a misunderstanding of the ecological consequences of effects. Risk scores, which are discrete values, do not reflect the uncertainty of the input data, and in some instances, fall on one of the extremum of the uncertainty distribution. Therefore, rather than presenting the calculated risk scores without uncertainty analysis, we present the median values of uncertainty distributions as final risk scores.

Uncertainty assessment with Monte Carlo simulation allows calculations to be made with a range of values rather than discrete values. In many cases, values for variables in the model are not precisely known. Instead, the variable is represented by a range of values and a probability distribution. The software application Crystal Ball® selects values (based on the assigned probability distributions) for each variable and uses these values to calculate risk scores. It was configured to repeat this process 1000 times, which appeared to be sufficient to represent the full potential range of risk scores.

We used an approach similar to that employed by Hart Hayes and Landis (2004) and Colnar and Landis (2007) to characterize the uncertainty of each variable categorically – as low, medium, or high, depending on the reliability of the data used to determine the variable's rank. In cases where data sources explicitly state the uncertainty present in the data, we used this statement as a guide for uncertainty distributions. In other cases, we used the best available information to make uncertainty assignments. See Supplemental Section 1 for more details. Expert opinion, included as supporting information, sometimes was in conflict. This was resolved by giving equal probability of effects occurring or not occurring when conflicts occurred.

We incorporated uncertainty of each variable into the model and used the Crystal Ball® risk-analysis software application to perform Monte Carlo simulations. Based on observation of the formation of uncertainty distributions as simulations progressed, it was evident that 1000 iterations were sufficient to develop an accurate representation of the range of possible results.

4. Results

Results of the risk assessment are relative risk scores for three categories – invasive plant species, rare or endangered plant species, and ecoregions. Risk scores are given in parentheses. Refer to the Supplemental Section 2 for risk score distributions. *Elaeagnus angustifolia* (260) and *R. cathartica* (244) present the greatest risk to all rare species in all ecoregions and all habitat types. *Elaeagnus umbellata* (151), *A. petiolata* (77), *Phragmites australis* (79), and *Lonicera maackii* (72) have moderate risk scores, while *Hypericum perforatum* (7) and *Coronilla varia* (5) present the lowest risk to all rare species in all ecoregions and habitat types (Fig. 2).

In grasslands, *E. angustifolia* presents the highest risk, followed distantly by *E. umbellata*. *H. perforatum* and *R. cathartica* present slight risk in grasslands (Fig. 3). *R. cathartica* presents the highest risk to forest and woodland communities, followed by *L. maackii*,

Author's personal copy

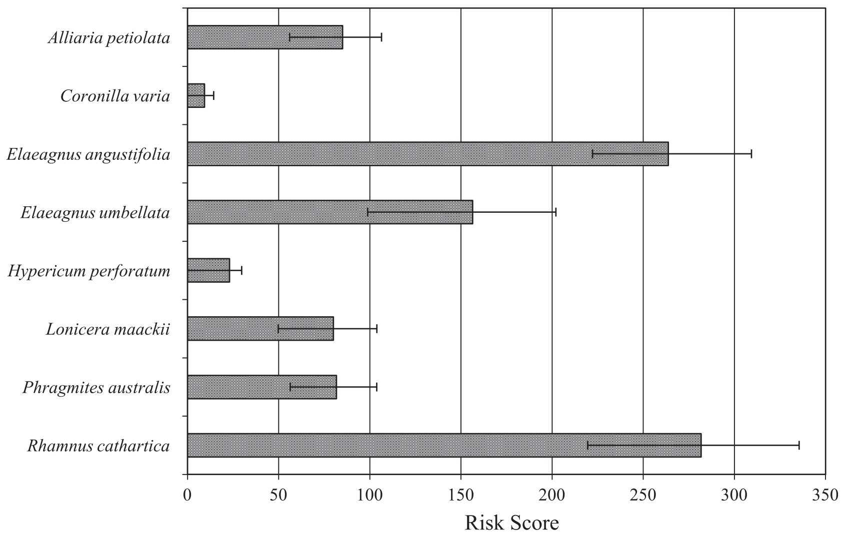


Fig. 2. Median risk scores for invasive plants, Error bars show 1 standard deviation from the mean, as found by Monte Carlo simulation.

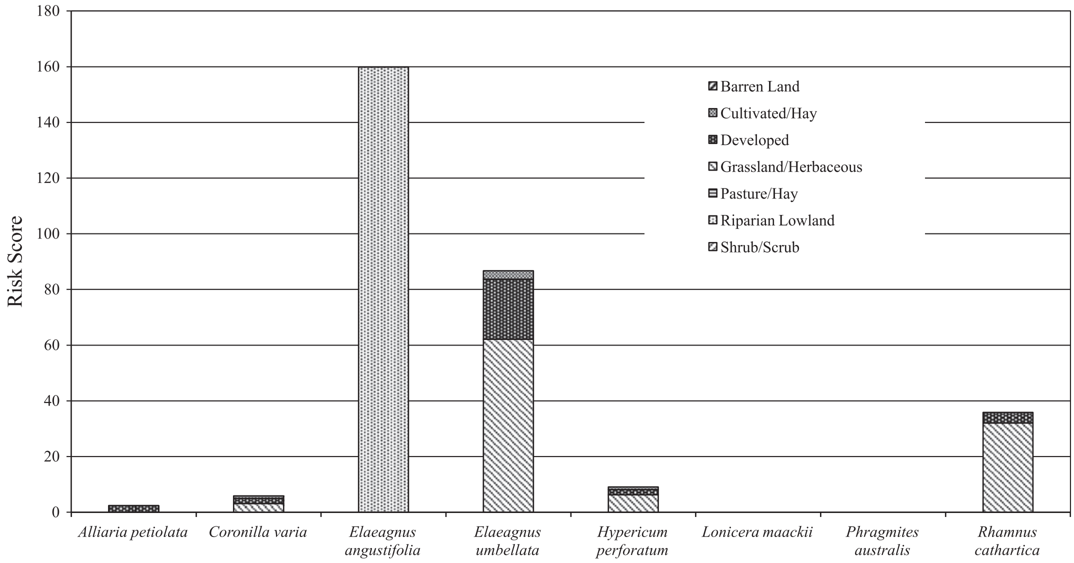


Fig. 3. Median risk scores for species that invade barrens, cultivated areas, developed, grassland, pastures, riparian, and shrub habitat types. The score presented for *E. angustifolia* represents the proportion of Riparian lowland that corresponds with these habitat types.

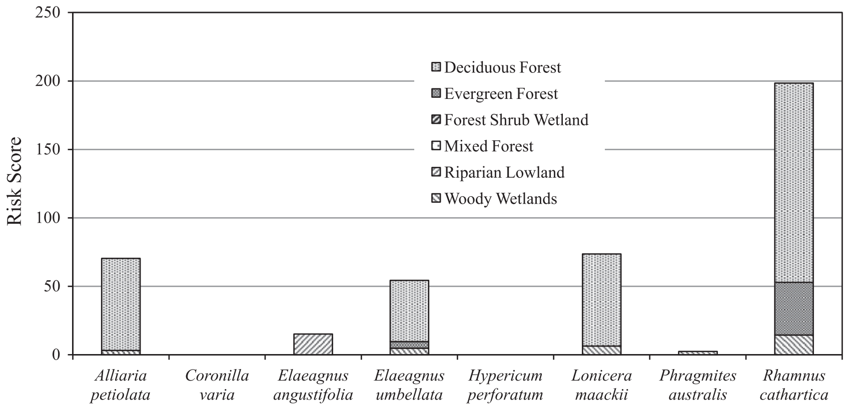


Fig. 4. Median risk scores for species that invade woodland and forest habitat types. The score for *E. angustifolia* represents the proportion of Riparian lowland that corresponds with these habitat types.

Author's personal copy

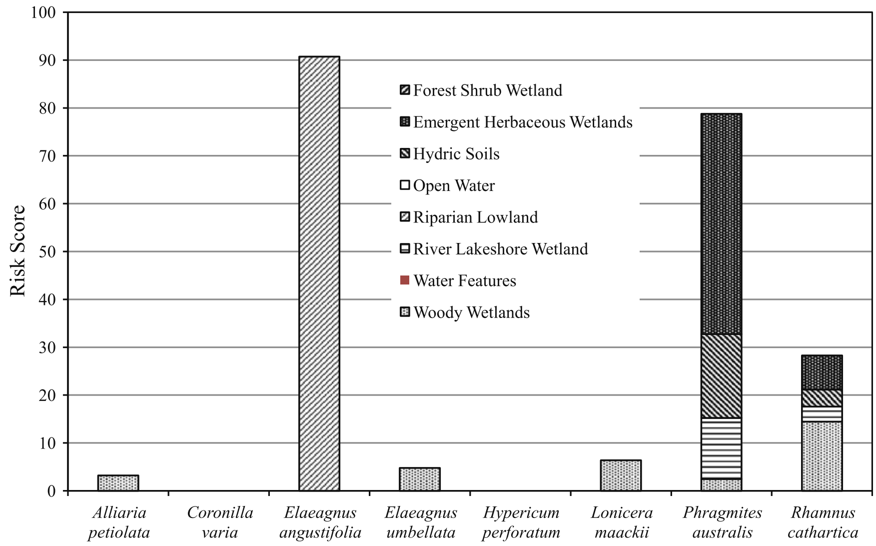


Fig. 5. Median risk scores for species that invade wetland and open water habitats. The score for *E. angustifolia* represents the proportion of Riparian lowland that corresponds with these habitat types.

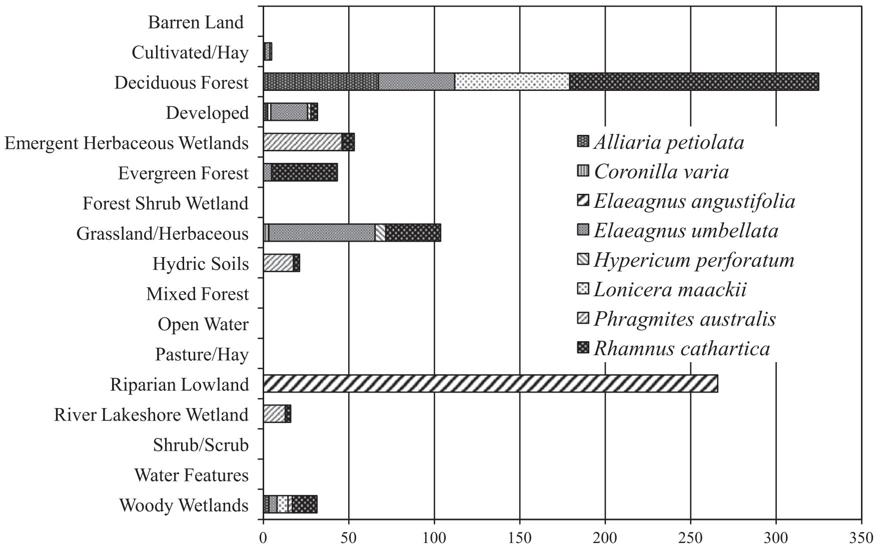


Fig. 6. Risk scores for all habitat types from all non-indigenous invasive plants, indicating the contribution each invasive species makes to risk scores in habitat types.

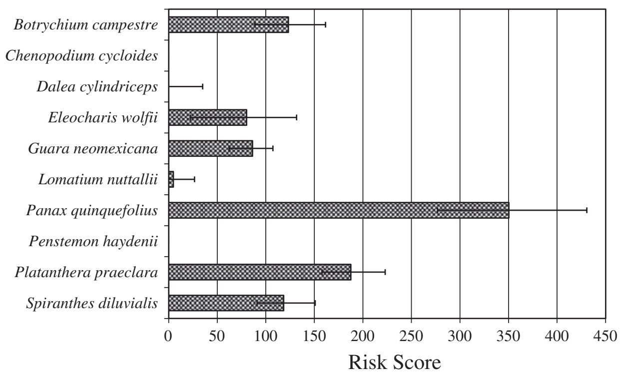


Fig. 7. Median risk scores for rare species from all invasive species in all ecoregions and habitats. Error bars indicate one standard deviation from the mean.

A. petiolata, and *E. umbellata* (Fig. 4). *E. angustifolia* and *P. australis* present the greatest risks in open and herbaceous wetland habitats (Fig. 5). *R. cathartica*, *L. maackii*, *A. petiolata*, and *P. australis C. varia* present the highest risk to forest and woody wetlands. Among habitat types, deciduous forests have higher risk than other habitat types, and the risk comes from the invasive plants *A. petiolata*, *E. umbellata*, *L. maackii*, and *R. cathartica* (Fig. 6).

Of the rare species considered, *Panax quinquefolius* (343) has the highest score, followed by *P. praeclara* (186). *B. campestre* (113), *S. diluvialis* (107), *Gaura neomexicana* ssp. *coloradensis* (77), and *Eleocharis wolffii* (64) follow with moderate scores (Fig. 7). The species with the negligible risk scores are *Lomatium nutallii* (5), *Delea cylindriceps* (0), *Chenopodium cycloids* (0), and *Penstemon haydenii* (0).

An examination of the contribution from each invasive species to risk scores of each rare species (Fig. 8) shows that the invasive species *A. petiolata* and *L. maackii*, each of which have relatively low risk scores by themselves, both contribute significantly to the high risk score of *P. quinquefolius*.

The Western Corn Belt Plains have the greatest risk (363), followed by the Western High Plains (217) and the Nebraska Sand Hills (198). The Northwestern Great Plains have moderate risk

Author's personal copy

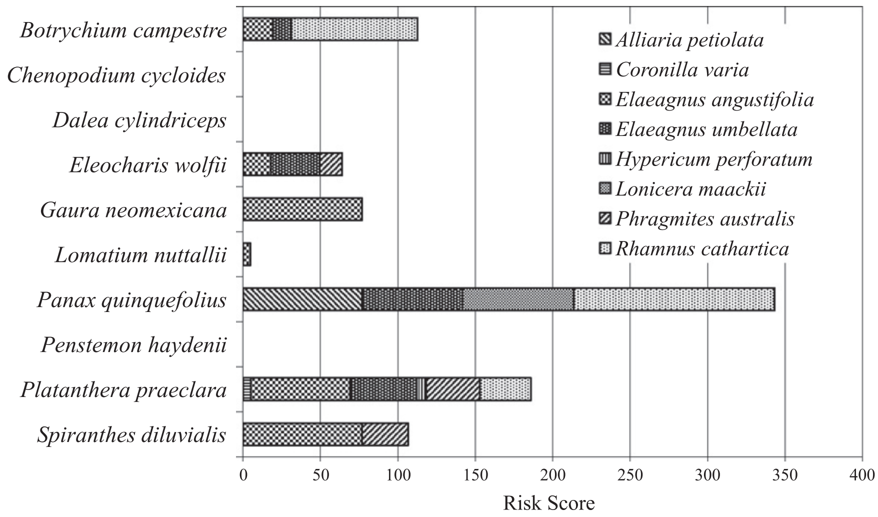


Fig. 8. Contributions from invasive species to the risk scores of rare species. All values are the median output resulting from Monte Carlo simulation. Note that for some rare species, the sum of values reported here is slightly less than that reported in Fig. 7. This is because the sum of the medians for each pair of rare and invasive species is reported here, whereas the median for each rare species and all invasive species is reported in Fig. 7.

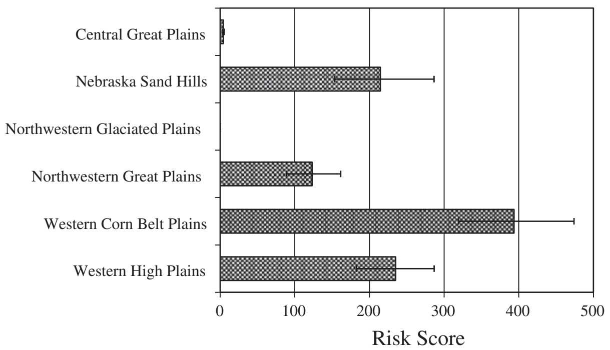


Fig. 9. Median risk scores for ecoregions in Nebraska. Error bars show one standard deviation from the mean, as found by Monte Carlo simulation.

(114), and the Central Great Plains (4) and Northwestern Glaciated Plains (0) have negligible scores (Fig. 9).

5. Discussion

These results show that of the invasive species analyzed, those that invade grassland tend to have higher risk scores, which is consistent with the frequent occurrence of these rare species in grasslands. While woodland habitats tend to have lower risk scores than grasslands, the rare species in woodlands have relatively high risk scores because numerous species invade both grassland and woodland. Risk scores from these species, in combination with those that exclusively invade woodlands, add up to create the relatively high risk scores. In addition, these results show that some invasive plant species with relatively low risk scores contribute significantly to the risks of some rare species, and thus should be considered priorities for management.

Invasive species of wetland communities tend to have relatively low risk scores as compared to invaders of other habitat types. While the risk scores for wetlands are relatively low, this does not indicate that wetland species are not at risk from invasive species. This too is consistent with the fact that few rare species included in analysis are wetland species. Furthermore, *E. angustifolia*, which invades Riparian lowland communities, likely presents an additional threat to the overall threat posed to rare species that reside in wetland communities.

6. Conclusions

The risk assessment presented herein provides insight into which invasive plants present the greatest threats to rare plants in Nebraska, which rare plants are at the greatest risk from invasive plants, and it shows how these risks are distributed throughout the state. While the scope of this analysis was limited to one U.S. state, the methodology can be adapted to other regions and scales, and to include different taxonomic groups, and other biological sources of risk. This type of analysis could also be used as a tool to help determine how invasive species management resources should be distributed regionally. It also highlights some strengths and weaknesses of using geospatial land cover data for ecological assessments, and provides insight into what additional data needs to be gathered in order to improve risk assessments of invasive species.

One advantage this approach offers is that risks to specific rare species can be explored in detail. Many invasive species assessments consider only vague end points, such as biodiversity or grazing productivity. The Relative Risk Model presents an approach that can be carefully analyzed and adapted to include other variables. A disadvantage of this approach, however, is that it is time consuming and requires some expert knowledge.

This risk assessment broadens the scope of applications of risk assessment to invasive species in a regional framework by including multiple sources (invasive species) and endpoints (rare species). The widespread availability of geospatial data, improvements in data collection, and advanced data analysis techniques make it possible to apply conventional risk assessment methods to this risk scenario.

Improvements in data collection methods, including satellite remote sensing, have provided more detailed habitat datasets that reflect ecologically relevant entities. These include, but are not limited to the USGS National Land Cover Dataset, National Wetlands Inventory data, and SSURGO data. Although these data sets were useful, some limitations were apparent, the most problematic being the inability to distinguish habitat types at a fine enough scale to differentiate the potential for co-occurrence between sources and invasive species. These could be addressed with improved ecological modeling of suitable habitats for invasive and

Author's personal copy

rare species, by increased categorical resolution of habitat categories, or with expert opinion, as demonstrated here.

The use of Global Positioning Systems (GPS) to document the locations of rare or endangered species presents the opportunity to analyze data on rare species geographically. Rather than relying upon literature to determine which habitat types are occupied by rare species (which may or may not correspond with the land cover types presented by the land cover datasets), geospatial data analysis permits the characterization of species-habitat associations in more explicit terms. Additionally, uncertainty in the GPS and habitat data can easily be incorporated into the model.

By incorporating spatial data, we were able to address spatial ecological designations such as ecoregions, in combination with geopolitical boundaries. The importance of geopolitical boundaries cannot be overstated because they often are the entities to which specific management strategies and resources are supplied.

Future applications of risk assessment will be improved if efforts to control invasive plants and efforts to promote rare species are incorporated into the model. With the exception of acknowledging the use of biological control agents for *H. perforatum*, we did not incorporate management efforts into the model. In addition, attempts to enhance existing populations of rare species are underway, such as the ongoing efforts to establish larger populations of *P. praeclara* (Fritz et al., 1992) in Nebraska. Characterizing and incorporating this information could improve the model.

While this approach may be useful for scientists and stake holders in regions outside the study area, especially in regions with similar stressor-habitat combinations and stressor-habitat-endpoint combinations, the results of this risk assessment should only be interpreted within the parameters of the risk assessment. Finally, a low risk score does not indicate that a species may not need intensive management – it merely indicates that the species has low risk within the parameters of this risk assessment.

Acknowledgements

We are grateful to the many individuals who contributed both directly and indirectly to this research. Thanks especially to Rick Schneider for reviewing the manuscript. This research was made possible with the financial support of the Center for Great Plains Studies, the Nebraska Game and Parks Commission, and the Nebraska Environmental Trust. Thanks also go to the Institute of Environmental Toxicology, Huxley College of the Environment at Western Washington University for training and support. The Nebraska Cooperative Fish and Wildlife Research Unit is jointly supported by a cooperative agreement between the United States Geological Survey, the Nebraska Game and Parks Commission, the University of Nebraska–Lincoln, the United States Fish and Wildlife Service, and the Wildlife Management Institute.

Appendix A

Invasive species-habitat-effects table (see Table A1).
Rare species-habitat type associations (see Table A2)

Table A1
Potential consequences resulting from the invasion of non-indigenous plants in habitat types. Lettered boxes indicate that the pathway for effects exists, whereas blank boxes indicate that there is no pathway. R = Alters resource allocation; S = Alters stand structure; Rn = Alters recruitment of native species; and M = Forms monotypic stands at the exclusion of other species.

	Invasive plant species (stressors)			
	Alliaria petiolata	*Coronilla varia*	*Elaeagnus angustifolia*	*Elaeagnus umbellata*
Barren land (rock/sand/gravel)	–	R, Rn, M	–	R, S, Rn, M
Cultivated/hay	–	R, Rn, M	–	R, S, Rn, M
Deciduous forest	R, Rn, M	–	–	–
Developed	–	R, Rn, M	–	R, S, Rn, M
Emergent Herbaceous Wetlands	–	–	–	–
Evergreen forest	R, Rn, M	–	–	–
Grassland/herbaceous	–	R, Rn, M	–	R, S, Rn, M
Mixed forest	R, Rn, M	–	–	–
Open water	–	–	–	–
Pasture/hay	–	R, Rn, M	–	R, S, Rn, M
Shrub/scrub	R, Rn, M	–	–	R, Rn, M
Woody wetlands	R, Rn, M	–	–	–
Forest shrub wetland	R, Rn, M	–	–	–
River/Lakeshore Wetland	–	–	–	–
Water Features	–	–	–	–
Hydric soils	–	–	–	–
Riparian lowland	–	–	R, S, Rn, M	–
	Hypericum perforatum	*Lonicera maackii*	*Phragmites australis*	*Rhamnus cathartica*
Barren land (rock/sand/gravel)	R, Rn, M	–	–	–
Cultivated/hay	R, Rn, M	–	–	–
Deciduous forest	–	R, S, Rn, M	–	R, S, Rn, M
Developed	R, Rn, M	–	–	–
Emergent Herbaceous Wetlands	–	–	R, S, Rn, M	–
Evergreen forest	–	R, S, Rn, M	–	R, S, Rn, M
Grassland/herbaceous	R, Rn, M	–	–	–
Mixed forest	–	R, S, Rn, M	–	R, S, Rn, M
Open water	–	–	–	–
Pasture/hay	R, Rn, M	–	–	R, S, Rn, M
Shrub/scrub	R, Rn, M	–	–	–
Woody wetlands	–	R, S, Rn, M	–	R, S, Rn, M
Forest shrub wetland	–	R, S, Rn, M	–	R, S, Rn, M
River/Lakeshore Wetland	–	–	R, S, Rn, M	–
Water features	–	–	R, S, Rn, M	–
Hydric soils	–	–	R, S, Rn, M	–
Riparian lowland	–	–	–	–

Author's personal copy

Table A2
Categories for rare species-habitat type associations. A value of 0 indicates that the data had no association, while a value 0.0 indicates that the data had an association of <0.05. An * indicates that published literature suggest a possible association, so these categories were included with a null rank, with uncertainty assignments appropriate for the sample size of the rare species occurrence records.

	Rare species (endpoints)									
	Botrychium campestre	*Chenopodium cycloides*	*Dalea cylindriceps*	*Eleocharis wolfii*	*Gaura neomexicana*	*Lomatium nuttallii*	*Panax quinquefolius*	*Penstemon haydenii*	*Platanthera praeclara*	*Spiranthes diluvialis*
Barren land (rock/sand/gravel)	0	0	0	0	0	0.2	0	0.0	0	0
Cultivated/hay	0	0	0	0	0	0	0	0	0.1	0
Deciduous forest	0.6	0	0	0.0	0	0	0.8	0	0.0	0
Developed	0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0
Emergent Herbaceous Wetlands	0	0	0	0.1	0.3	0	0	0.0	0.1	0.4
Evergreen forest	0.4	0	0	0	0	0	0	0.0	0	0
Grassland/herbaceous	0	1.0	1.0	0.9	0.5	0.8	0	0.9	0.7	0.4
Mixed forest	0*	0	0	0	0	0	0	0.0	0	0
Open water	0	0	0	0.0	0.0	0	0	0.0	0.0	0
Pasture/hay	0	0*	0*	0	0	0*	0	0	0.0	0*
Shrub/scrub	0	0	0	0	0	0	0	0	0.0	0
Woody wetlands	0*	0	0	0.0	0	0	0.1	0.0	0.0	0
Forest shrub wetland	0*	0	0	0	0.0	0	0	0	0	0
River/Lakeshore Wetland	0	0	0	0.0	0.1	0	0	0.0	0.1	0.1
Water features	0	0	0	0.0	0	0	0	0.0	0	0
Hydric soils	0	0	0	0.0	0	0	0	0	0.1	0.2
Riparian lowland	0.5	0	0	0.4	0.9	0.3	0.2	0.0	0.7	1.0

Appendix B

Risk score computation for ecoregions Eq. (B.1), endpoints Eq. (B.2), and habitats Eq. (B.3). Scores for each are calculated by summing the scores.

$$RSS_{ecoregion_j} = \sum S_{ij} \times H_{ij} \times E_{ijkl} \times X_{ilm} \quad \text{(B.1)}$$

for i = Central Great Plains…Western High Plains

$$RRS_{endpoint_m} = \sum (S_{ij} \times H_{ij} \times E_{ijkl} \times X_{ilm}) \quad \text{(B.2)}$$

for m = *B. campestre*…*S.* diluvialis

$$RRS_{habitat_l} = \sum (S_{ij} \times H_{ij} \times E_{ijkl} \times X_{ilm}) \quad \text{(B.3)}$$

for l = Barren land…Riparian lowland, *RRS* relative risk score for series i, j, m, or l, S_{ij} source (invasive species) ranks in ecoregions, H_{il} habitat ranks in ecoregions, E_{ijkl} effects in ecoregions for stressor-effect-habitat combination, X_{ilm} exposure filter in ecoregions for each habitat-endpoint combination, i ecoregion series (Central Great Plains…Western High Plains), j invasive species series (*A. petiolata*…*R. cathartica*), k effects series (resource allocation…spatial arrangement), l habitat series (barren land…Riparian lowland), m rare and endangered species series (*B. campestre*…*S. diluvialis*), ite/seamless/viewer.htm.

Appendix C. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2010.05.015.

References

Allen, C.R., Johnson, A.R., Parris, L., 2006. A framework for spatial risk assessments: potential impacts of nonindigenous invasive species on native species. Ecology and Society 11 (1), 39. <http://www.ecologyandsociety.org/vol11/iss1/art39/>.

Anderson, M.C., Adams, H., Hope, B., Powell, M., 2004. Risk assessment for invasive species. Risk Analysis 24, 787–793.

Bartell, S.M., Nair, S.K., 2004. Establishment risks for invasive species. Risk Analysis 24, 833–845.

Chapman, S.S., Omernik, J.M., Freeouf, J.A., Huggins, D.G., McCauley, J.R., Freeman, C.C., Steinauer, G., Angelo, R.T., Schlepp, R.L., 2001. Ecoregions of Nebraska and Kansas (color poster with map, descriptive text, summary tables, and photographs): Reston, Virginia, US Geological Survey (map scale 1:1950,000).

Colnar, A.M., Landis, W.G., 2007. Conceptual model development for invasive species and a regional risk assessment case study: the European green crab, *Carcinus maenas*, at Cherry Point, Washington, USA. Human and Ecological Risk Assessment 13, 120–155.

Cowardin, L.M., Carter, V., Golet, F., LaRoe, E., 1979. Classification of Wetlands and Deepwater Habitats of the United States. US Fish and Wildlife Service, 103 pp.

Dawson, W., Burslem, D.F.R.P., Hulme, P.E., 2009. The suitability of weed risk assessment as a conservation tool to identify invasive plant threats in East African rainforests. Biological Conservation 142, 1018–1024.

Di Castri, F., 1989. History of biological invasion with special emphasis on the Old World. In: Drake, J.A., Mooney, H.A., di Castri, F., Groves, R.H., Kruger, F.J., Rejmanek, M., Williamson, M. (Eds.), Biological Invasions: A Global Perspective. John Wiley and Sons, New York, pp. 1–30.

Elton, C.S., 1958. The Ecology of Invasions by Animals and Plants. Methuen, London.

Fritz, M., Stubbendieck, J., Jobman, W., 1992. Blowout Penstemon (*Penstemon haydenii* S. Wats.) Recovery Plan. US Fish and Wildlife Service, Denver.

Hart Hayes, E., Landis, W.G., 2004. Regional ecological risk assessment of a near shore marine environment: Cherry Point, WA. Human and Ecological Risk Assessment 10, 299–325.

Kaul, R.B., Sutherland, D., Rolfsmeier, S., 2006. The Flora of Nebraska. School of Natural Resources, University of Nebraska-Lincoln, Lincoln, NE, USA.

Keller, R.P., Lodge, D.M., Finnoff, D.C., 2007. Risk assessment for invasive species produces net bioeconomic benefits. Proceedings of the National Academy of Sciences 104, 203–207.

Kolar, C.S., Lodge, D.M., 2002. Ecological predictions and risk assessment for alien fishes in North America. Science 298, 1233–1236.

Landis, W.G., 2004. Ecological risk assessment conceptual model formulation for nonindigenous species. Risk Analysis 24, 847–858.

Morse, L.E., Randall, J.M., Benton, N., Hiebert, R., Lu, S., 2004. An Invasive Species Assessment Protocol: Evaluating Non-native Plants for their Impact on Biodiversity. Version 1. NatureServe, Arlington, VA, USA.

National Research Council (NRC), 2002. Predicting Invasions by Nonindigenous Plants and Plant Pests. National Academy of Sciences, Washington, DC, USA.

Natural Resources Conservation Service (NRCS), Soil Survey Division, United States Department of Agriculture, 2006. Soil Data Viewer 5.1 User Guide. 60 pp. <http://soildataviewer.nrcs.usda.gov/documents/Soil_Data_Viewer_5_1_User_Guide.pdf>.

Natural Resources Conservation Service (NRCS), United States Department of Agriculture, 2007a. Soil Survey of Nebraska [computer files]. <http://soildatamart.nrcs.usda.gov/Survey.aspx?State=NE>.

Natural Resources Conservation Service (NRCS), United States Department of Agriculture, 2007b. Official Soil Series Descriptions (OSD). <http://soils.usda.gov/technical/classification/osd/index.html>.

Author's personal copy

NatureServe, 2007. NatureServe Explorer: An Online Encyclopedia of Life [web application]. Version 6.2. NatureServe, Arlington, VA. <http://www.natureserve.org/explorer> (accessed 25.01.08).
Nebraska Natural Heritage Program, 2007. Nebraska Heritage Data [computer file]. Nebraska Game and Parks Commission, Lincoln, NE, USA.
Office of Technology Assessment, 1993. Harmful Non-indigenous Species in the United States. US Congress, OTA-F-565. US Government Printing Office, Washington, DC.
Omernik, J.M., 1987. Ecoregions of the conterminous United States. Map (scale 1:7, 500, 000). Annals of the Association of American Geographers 77, 118–125.
Pheloung, P.C., Williams, P.A., Halloy, S.R., 1999. A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. Journal of Environmental Management 57, 239–251.
Pimentel, D., Lach, L., Zuniga, R., Morrison, D., 2000. Environmental and economic costs of non-indigenous species in the United States. BioScience 50, 53–65.
Ruiz, G.M., Fofonoff, P., Carlton, J.T., Wonham, M.J., Hines, A.H., 2000. Invasions of coastal marine communities in North America: apparent patterns, processes, and biases. Annual Review of Ecology and Systematics 31, 481–531.
Schneider, R., Humpert, M., Stoner, K., Steinauer, G., 2005. The Nebraska Natural Legacy Project: A Comprehensive Wildlife Conservation Strategy. The Nebraska Game and Parks Commission, Lincoln, NE, USA.
United States Environmental Protection Agency (USEPA), 1998. Guidelines for Ecological Risk Assessment. EPA/630/R-95/002F, Washington, DC, USA.
United States Fish and Wildlife Service (USFWS), 2007a. Classification of Wetlands and Deepwater Habitats of the United States. US Department of the Interior, Fish and Wildlife Service, Division of Habitat and Resource Conservation, Washington, DC. FWS/OBS-79/31. <http://wetlandsfws.er.usgs.gov/NWI/download.html>.
United States Fish and Wildlife Service (USFWS), 2007b. Wetlands and Deepwater Habitats Classification, National Wetlands Inventory Mapping Code Description Internet Page. <http://wetlandsfws.er.usgs.gov/NWI/webatx/atx.html>.
United States Geological Survey (USGS), 2007. The National Map Seamless Server. <http://seamless.usgs.gov/webs> (accessed 27.04.07).

Glossary

Effects: mechanisms by which stressors may affect endpoints
Endpoint: imperiled plant species included in the analysis
Exposure: indicates that a stressor potentially can affect an endpoint
Source ranks: the magnitude of occurrences of stressors in this application of the Relative Risk Model
Stressor: non-indigenous invasive species included in this application of the Relative Risk Model