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RESEARCH PAPER

Using map algebra to determine the mesoscale distribution of invasive plants: the case of *Celastrus orbiculatus* in Southern Illinois, USA

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Abstract Since its introduction into North America in the late 19th century, *Celastrus orbiculatus* (Thumb.) has become a serious ecological threat to native ecosystems. Development of a method to accurately map the occurrence of invasive plants, including *C. orbiculatus*, would greatly assist in their assessment and control. Using an innovative map regression model, we predicted 85% of presence and absence of *C. orbiculatus* within our study area. We identify environmental characteristics associated with *C. orbiculatus* and demonstrate the use of this information to predict occurrence of *C. orbiculatus* across a broad area in Southern Illinois, USA. Presence and absence information were obtained at sample points within discrete areas of *C. orbiculatus* occurrence. Forest cover, elevation, slope gradient and aspect, soil pH and texture, distance to nearest road, and potential annual direct incident radiation were recorded for invaded and adjacent non-invaded areas. Presence of oak, elevation, slope gradient, soil pH, soil texture, and distance to road were significant factors associated with the presence or absence of *C. orbiculatus*. Probability of occurrence of *C. orbiculatus* was highest on gently sloping interfluves with successional forest canopy not dominated by oak, and less acidic, mesic soil. A logistic regression model was developed and extrapolated over a raster GIS data layer using map algebra to predict current invasion throughout the study area. The model correctly predicted at least 85% occurrence of *C. orbiculatus*. When combined with logistic regression, map algebra is a potentially powerful tool for evaluating the spatial distribution of invasive plants provided sound statistical principles are applied in extrapolating validated regression models.

Keywords *Celastrus orbiculatus* · Invasive species · Landscape · Map algebra · Spatial extrapolation

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Introduction

The invasion dynamics of exotic species depend to a large extent on characteristics of the landscape (Planty-Tabacchi et al. 1996; Garcia-Robledo and Murcia 2005; Thomas et al. 2006). Landscape-scale factors interact with more local biotic and abiotic factors such as neighbor density, native species diversity and soil pH. Together, these factors can allow exotic species to become abundant and persistent differentially within the landscape, and contribute to their potential nuisance or pest status (Rand et al. 2004; Knight and Reich 2005). Plant traits favoring invasion include lack of controlling natural enemies, ability to effectively compete in a new ecosystem, availability of artificial or disturbed habitats, and intrinsic adaptability to novel conditions (Hierro et al. 2005; Lloret et al. 2005; Pimentel et al. 2000). Disturbance frequently favors invasion (Hobbs 1989; Hobbs and Huenneke 1992; Orians 1986) as environments subject to fluctuations in resource supply offer microhabitats available for exploitation compared to environments with stable resource supply (Rejmanek and Richardson 1996). An invading species may therefore be able to exploit unused resources even when its ecology is not fundamentally different from that of indigenous species (Davis et al. 2000).

While the risks and losses associated with non-native invasive species are well documented, control of them is less certain. Monitoring of natural areas, such as scouting for plants and systematic regional surveys, may enhance control of invasion (Dreyer 1994; Rudis 2005). Identification of environmental factors that facilitate a particular species' invasion is necessary to assist early intervention (Silveri et al. 2001). Landscape-scale information on areas impacted by invasive species are particularly vital (Byers et al. 2002; Rudis 2005; Saura and Carballal 2004), particularly when monitoring high-risk areas (Stohlgren et al. 2001).

Advances in Geographic Information Science and the availability of Geographic Information System-based data expand the possibilities for accurate mapping of invasive species at landscape scales through their ability to extrapolate ecological and other factors determining habitat suitability across geographic space. Tomlin (1990) in *Geographic Information Systems and Cartographic Modeling* first described the possibility of determining the values in one raster (cell-based) data layer from values in corresponding cells in other data layers. Since then, this technique has been termed 'map algebra.' For example, Pinter and Vestal (2005) have used this approach to determine the distribution of landslide risks in California's Santa Cruz Island. Heine et al. (2004) used logistic regression of raster-based data to determine the location of stream channels. Their approach was far more accurate than use of existing US Geological Survey topographic maps. Map algebra, specifically in the form of raster regression, has the potential to accurately map the distribution of invasive plants in a similar manner. Further, map algebra is a predictive rather than explanatory use of regression analysis and therefore allows the location of a phenomenon to be predicted from factors that may or may not bear a causal relationship to the phenomenon being mapped, or that may exhibit multicolinearity. However, it requires that predictor variables are represented as, or can be converted to, raster data layers so that their values in specific raster cells can influence the estimation of predictions in those same cells.

The goal of this study was to identify the current distribution of *C. orbiculatus* within the study area. The objectives were to: (1) identify significant associations between *C. orbiculatus* and environmental parameters; and (2) to employ spatial extrapolation of significant associations in prediction of presence and absence of *C. orbiculatus* within the study area. We employed map algebra as a means to construct an accurate map of the current occurrence of the invasive plant *Celastrus orbiculatus* Thumb. in a study area in Southern Illinois, USA. In doing so, we illustrate the potential, as well as the limitations, of this innovative approach as applied to *C. orbiculatus*, and invasive species more generally.

The test case: *Celastrus orbiculatus*

Celastrus orbiculatus (Thunb. Celastraceae), also known as Oriental bittersweet, Asian bittersweet, and round-leaved bittersweet, is a deciduous liana native to southeast Asia. The habitat of *C. orbiculatus* in Asia is described as ‘thickets and hillsides’ (Patterson 1974). Since its introduction in the US in the late 19th century, it has become invasive and an ecological and economic threat to native ecosystems, particularly in disturbed temperate forest areas (McNab and Meeker 1987; Tibbetts 2000). Suitable habitat is described variously as alluvial woods, roadsides, thickets, and old home sites (Tennessee and Southeast Exotic Pest Plant Council 2004; Virginia Department of Conservation and Recreation 1999); a variety of forest types (Illinois Natural History Survey 1990); and forest edges, woodlands, early successional fields, hedgerows, coastal areas, and salt marsh edges (Plant Conservation Alliance 1997). *Celastrus orbiculatus* is naturalized in at least 21 of 33 states where it has been introduced (Patterson 1974) and currently occurs from the New England states south to North Carolina, and westward to Illinois (Invasive Plant Atlas of New England 2005; Plant Conservation Alliance 1997). In North America it is listed within states variously as ‘widespread and invasive,’ ‘strongly invasive and widespread,’ a ‘serious threat,’ and an ‘obligate ruderal’ (Missouri Botanical Garden 2002; New Jersey Native Plant Society 2005; Ohio Department of Natural Resources 2004; Rhode Island Wild Plant Society 2005; Pennsylvania Department of Conservation and Natural Resources 2005; Wisconsin Botanical Information System 2005). Systematic state-wide surveillance has not been conducted, and the extent of invasion within North America is therefore unknown. For example, in Massachusetts, *C. orbiculatus* is reported in each of 14 counties; however its abundance, density and spatial extent in each county is not reported (Conservation New England 1998). In Ohio, it is reported in 15 of 88 counties, likewise without estimation of density or spatial extent within counties (National Resources Conservation Service 2005). In Wisconsin it is reported as present at nine locations within two of 72 counties (Wisconsin Botanical Information System 2005).

Control of *C. orbiculatus*, which typically includes mechanical and chemical means, is too often unsuccessful (Dreyer 1988, 1994; Silveri et al. 2001). Additionally, Ellsworth et al. (2004) find *C. orbiculatus* seedlings originate from the current year’s seed input rather than from the seed bank and conclude that invasion may be limited if established plants are killed before fruits mature. Thus, by investigating landscape-level environmental characteristics associated with *C. orbiculatus*, as in this study, land managers may avoid costly invasions before they occur through targeting monitoring.

In Illinois, *C. orbiculatus* poses a serious threat to natural vegetation (Dreyer et al. 1987), and is listed as a ‘species of concern’ growing at locations throughout the state (Illinois Department of Natural Resources 2004). In this study, we investigated the invasion of *C. orbiculatus* across an approximately 1,500 ha forest landscape in and near Giant City State Park in southern Illinois, in relation to environmental factors. The study area consisted of mixed mesic forest types with a history of disturbance by human and natural processes. We identified environmental factors significantly associated with *C. orbiculatus* presence at known locations within the study area, and then used these as criteria to develop a probability map depicting the likelihood of its presence throughout the study area. The model was validated by collection of subsequent field observations. We tested the following null hypotheses: (1) *C. orbiculatus* is distributed randomly across the Giant City State Park forest landscape, and (2) landscape and local factors are unrelated to the distribution and invasion probability of *C. orbiculatus*.

Methods

Study area

Field research was conducted in Giant City Park (37.58° N 89.16° W, mean elevation 203 m asl), a state-owned natural area located within the unglaciated Shawnee Hills section of the Interior Plateau Province. Giant City Park is approximately 1,495 ha, and located in southeastern Jackson and northeastern Union counties, approximately 16 km SE of Carbondale, IL.

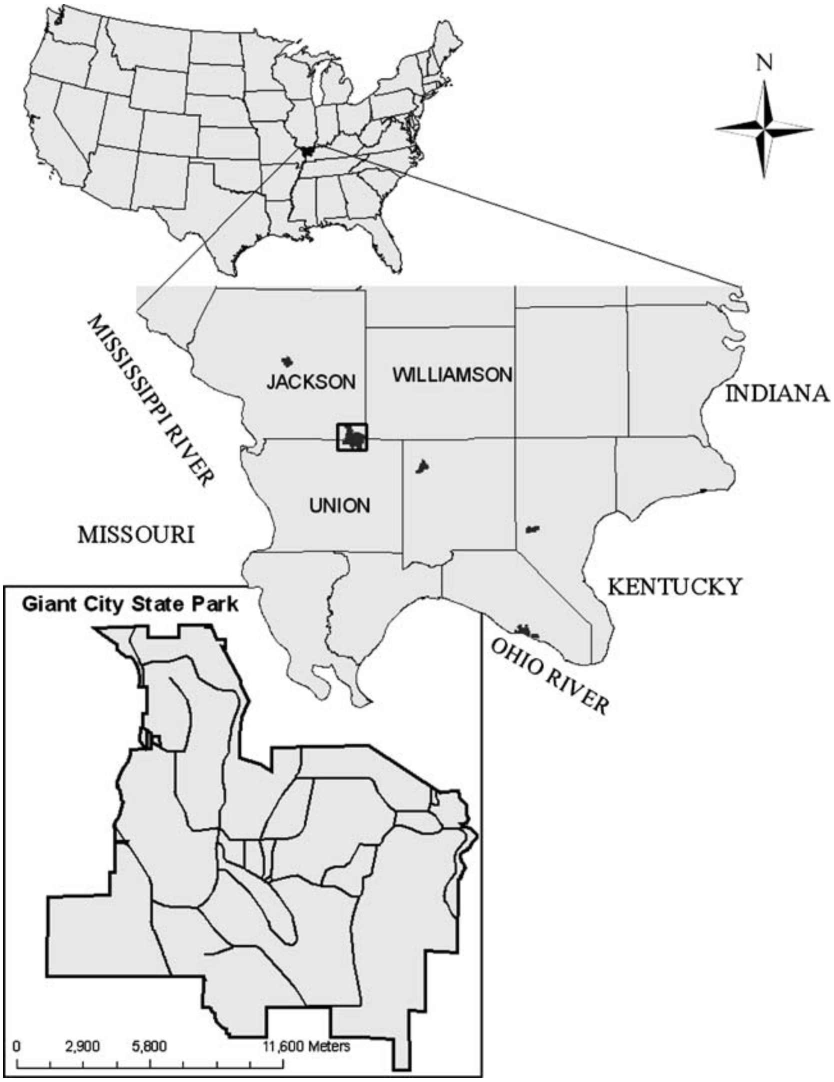


Fig. 1 Location of Giant City State Park within southern Illinois and the US

(Fig. 1). The Park rests entirely upon Pennsylvanian aged bedrock (Voigt and Mohlenbrock 1964) covered by Quaternary deposits of clay and sand (Davis 1987). The soils within Giant City Park consist of Hosmer complex soil (Davis 1987) and have historically been cultivated. Original forests and prairie of Giant City Park have been disturbed and fragmented by agricultural clearing. Mean annual temperature is approximately 13°C with mean July temperature of 24°C, and mean January temperature of 3°C (National Oceanic and Atmospheric Administration 2004). Average annual precipitation is 112 cm, the majority of which falls April–September (Herman et al. 1979). Landcover consists of xerophytic blufftop woods, dry slope woods, moist woods, wooded wetlands, bottomland woods, and old fields typical of the potential natural vegetation of SW Illinois (Voigt and Mohlenbrock 1964). In addition to *C. orbiculatus*, problematic exotics in Giant City Park include *Dioscorea oppositifolia* L., *Rosa multiflora* Thunb., and *Lonicera japonica* Thunb. (Thomas et al. 2006).

Sampling

Initial field reconnaissance was conducted in March 2004 for verification of reported locations of *C. orbiculatus* occurrence, and for exploration of possible additional occurrences. Sampling was conducted July–October 2004, with model validation (see below) conducted based upon field data collected in June 2005. Twelve *C. orbiculatus* invaded sites (patches) were selected for range of forest cover type and topographic conditions. One hundred seventeen sample points were placed among *C. orbiculatus* patches and an additional 117 points were placed within adjacent non-invaded areas ($N = 234$). Number of points per patch was randomly assigned. Points within patches were randomly placed to the left or right of 1–2 transects that were oriented to maximize spatial coverage of points along the transects. Number of transects varied according to patch size (e.g., large patches had two transects). Points were placed 5–10 m from transects and at 5–15 m intervals along transects depending on the cover type (e.g., distance between points was maximum in cover types with widely-spaced large trees). Sample points in non-invaded areas were selected by dividing a digital orthophoto quadrangle of Giant City Park into 500 m × 500 m grids and randomly selecting 15 grids. Within each grid, eight sample points were placed 15–20 m from the grid center and at 0/360°, 45°, 90°, 135°, 180°, 225°, 270° and 315° compass bearings.

Data regarding presence of *C. orbiculatus* and environmental characteristics were collected within 5 m of all points. Sample points within a patch were 15–45 m apart depending upon the size of trees in the neighborhood of the point. In all cases, points were located far enough apart to ensure that the same tree was not counted or measured twice between points. *Celastrus orbiculatus* was recorded as present if one or more stems were detected, otherwise it was recorded as absent. Oak (*Quercus* spp.) was categorized at each sample point as present if any of the four nearest trees in each of the four cardinal directions and greater than 10 cm diameter at breast height were oak. The following edaphic and topographic data were gathered at each point: slope gradient measured to the nearest degree from horizontal using a Suunto PM-5 clinometer; slope aspect measured to the nearest degree using a Suunto Challenger compass; slope position recorded as 'blufftop,' 'upperslope,' 'midslope,' or 'lowerslope' based on visual inspection; canopy cover measured by densiometer at breast height within each quarter according to Strickler's (1959) adjustment; and latitude/longitude measured by a global positioning system (GPS) device (Garmin eTrex). Slope gradient and aspect, and latitude information were used to calculate an index of potential annual direct incident radiation according to McCune and Keon (2002). Soil samples were collected from 7–8 locations within 5 m of each point and were analyzed for pH and texture. Elevation and distance to nearest road for all points were derived using a digital elevation model (US Geological Survey), and vector-format road coverages (US Geospatial Data Gateway) in a geographic information system (GIS) (ESRI 2005).

Data analysis

Preliminary to conducting logistic regression analysis, biserial correlation analysis was conducted to assess associations of slope gradient and aspect, slope position, oak presence, soil pH and texture, solar radiation index, elevation, and distance to nearest road with presence or absence of *C. orbiculatus* (SPSS Version 13.0). Correlations were examined to assess multicolinearity among environmental variables. Using all potential explanatory variables, a logistic regression model was constructed to maximize the percentage of points where the presence or absence of *C. orbiculatus* was correctly predicted. In order to conduct map algebra, a second logistic regression model was then constructed using only predictive variables that could be represented in raster form. This model was then used to determine the probably of occurrence of *C. orbiculatus* for each 30 m cell in the raster based on the digital elevation model. Finally, from this map a validation transect was chosen that showed a wide range of probabilities of occurrence varying from zero to one. Subsequent field work was performed to establish the presence or absence of *C. orbiculatus* along this transect.

Results

Environmental factors and *C. orbiculatus* presence/absence

Biserial correlations revealed significant relationships between environmental conditions and *C. orbiculatus*. Environmental conditions where *C. orbiculatus* was present were different from areas where it was absent. Paired *t*-tests revealed that elevation, distance to road, pH, percent clay, and potential global solar radiation were significantly higher ($P < 0.05$) on sites where *C. orbiculatus* was present compared to where it was absent, whereas slope gradient, slope aspect, percent sand, and percent silt were significantly lower (Table 1).

Simple linear correlation revealed significant relationships among several environmental variables (Table 2). Most important are the interrelationships among slope gradient, elevation and oak presence; slope gradient is negatively correlated with elevation in this dissected plateau landscape with high, flat interfluves and narrow steep valleys where oak predominates.

Logistic regression analyses revealed six environmental variables significantly associated with *C. orbiculatus* presence/absence: elevation, slope gradient, pH, oak presence/absence ($P < 0.001$), distance to road ($P < 0.005$) and percent clay ($P < 0.05$) (Table 3). The six-variable model had the lowest AIC value (111.534). The logit model correctly predicted 92.3% of the 234 observations. Results thus indicate occurrence of *C. orbiculatus* in association with high, flat interfluves having mesic, less acidic soil conditions and lacking oak.

Map algebra and probability mapping

For the purpose of developing a probability map of *C. orbiculatus* occurrence throughout Giant City Park and nearby areas using map algebra, an additional logistic regression model was developed using only variables for which data were readily obtainable in raster GIS format. That is, some significant environmental parameters identified in linear regression could not be included in map algebra methods because the data were not available in the necessary format. Although this results in some reduction in model power and predictive success, it is necessary because the probability of occurrence of *C. orbiculatus* in each raster cell can only be calculated if each predictor variable also has a value in each raster cell. Four raster-based explanatory variables were found to be significant: elevation, slope, distance to road, and radiation index (Table 4). The model of these four parameters correctly predicted presence/absence for 85% of the 234 sites. Thus, omission of the non-raster variables oak, pH, and percent clay, and the addition of radiation index, but which was not significant in the all variables model, resulted in a slight loss of predictive accuracy, from 92% to 85%, but permitted landscape-scale extrapolation using raster GIS.

The probability of *C. orbiculatus* occurring in each raster cell was calculated to produce a new

Table 1 *t*-Test of difference between means of environmental variables in *Celastrus* and non-*Celastrus* sites. $N = 234$ (117 *Celastrus* and 117 non-*Celastrus* sites)

Variables measured	*Celastrus* site			Non-*Celastrus* site			*t*	*P*
	Mean	SD	Range	Mean	SD	Range		
Elevation (m)	203.48	12.87	166.5–230	173.74	21.08	133.3–207	– 13.02	< 0.001
Slope gradient (°)	4.7	3.67	0–25	9.3	4.93	1–27	8.06	< 0.001
Distance to road (m)	127.94	105.35	0–411.95	83.38	80.22	0–360	– 3.64	< 0.001
pH	5.02	0.56	4–6.6	4.64	0.43	3.7–6.3	– 5.76	< 0.001
Canopy cover (%)	83.4	9.3	42.5–99.5	82.6	10.6	51.5–101	– 0.61	0.541
Radiation index	0.96	0.41	0.68–1.02	0.95	0.06	0.67–1.03	– 1.98	0.048
Sand (%)	5.2	5.65	0–29.31	7.3	8.57	0–35.95	2.22	0.027
Silt (%)	70.1	5.3	50–83.4	72.3	7.4	47.84–89.6	2.6	0.010
Clay (%)	24.7	5.3	14.3–43.9	20.4	5.5	10.4–38.5	– 6.08	< 0.001

Table 2 Correlation matrix including *C. orbiculatus* presence and environmental variables

Probability correlation	*Celastrus* presence/ absence	Elevation	Canopy cover	Slope gradient	Radiation index	Distance to road	pH	Oak presence	Sand	Silt
Celastrus presence/absence		< 0.001	0.541	< 0.001	0.048	< 0.001	< 0.001	< 0.001	0.027	0.010
Elevation	0.650		0.856	< 0.001	0.001	0.018	0.238	< 0.001	< 0.001	0.880
Canopy cover	0.040	– 0.012		0.209	0.701	0.064	0.119	0.937	0.553	0.663
Slope gradient	– 0.468	– 0.354	– 0.082		< 0.001	0.919	< 0.001	< 0.001	0.092	0.958
Radiation index	0.129	0.213	– 0.025	– 0.553		0.359	0.255	0.119	0.528	0.600
Distance to road	0.232	0.155	– 0.121	0.007	– 0.060		0.509	0.019	0.211	0.363
pH	0.354	0.077	0.102	– 0.407	0.075	– 0.043		< 0.001	0.364	0.861
Oak presence	– 0.565	– 0.313	– 0.018	0.400	– 0.109	– 0.142	– 0.359		0.113	0.092
Sand	– 0.144	– 0.313	0.039	0.111	0.041	– 0.082	0.060	0.108		< 0.001
Silt	– 0.168	0.010	– 0.029	– 0.003	– 0.034	– 0.060	0.011	0.109	– 0.654	
Clay	0.371	0.384	– 0.017	– 0.136	– 0.014	0.171	– 0.088	– 0.258	– 0.529	– 0.296

Pearson's *R* correlation coefficients are in the lower left; probability of greater *R* is shown in the upper right

raster layer (Fig. 2) by employing the logit equation based on Wrigley (1985):

$$P = 1/[1 + e^{(-(-10.50349+0.11549\text{ elevation } - \text{ }0.28621\text{ slope}+0.00721\text{distance to road}+0.00001\text{ radiation}))}] \tag{1}$$

where, P = probability of occurrence of *C. orbiculatus*. The resulting map of probabilities is shown (Fig. 3) and includes the boundaries of Giant City Park; the invaded and non-invaded sites used for model calibration and subsequent validation sites are shown for orientation and comparison. The distribution of probabilities among raster cells is bi-modal with few cells having a predicted probability near 0.5 (Fig. 4). This makes the prediction relatively insensitive to minor changes in predictor variables or errors in their measurement and thus increases predictive power.

Table 3 Results of the logistic regression model explaining occurrence of *Celastrus orbiculatus*

Model/variables	Regression coefficient	Wald Chi-square	Probability > Chi-square
Elevation	0.135	31.389	< 0.001
pH	2.322	15.316	< 0.001
Clay	0.112	5.038	0.025
Slope gradient	– 0.238	11.144	< 0.001
Distance to road	0.009	9.055	0.003
Oak presence	– 2.066	14.269	< 0.001
Intercept	– 38.298	34.585	< 0.001

N = 234, Chi-square = 96.148, Probability > Chi-square < 0.001, Pseudo R^2 (Cox and Snell = 0.623 and Nagelkerke = 0.831), AIC = 111.534, Percent correct prediction = 92.3%

Model validation

Subsequent field observations in June 2005 revealed 196 sites with and 242 sites without *C. orbiculatus* (Fig. 3). Eighty-eight percent of sites in which *C. orbiculatus* actually occurred were correctly identified in the probability map (Fig. 3) and 86% of sites not containing *C. orbiculatus* were correctly predicted. Overall predictive accuracy was 87%, slightly higher than the calibration model (Table 5). These results strongly support the predictive power of the

Table 4 Results of the logistic regression model based only on GIS raster layers for the prediction of occurrence of *Celastrus orbiculatus*

Variables	Regression coefficient	Wald Chi-square	Probability > Chi-square
Elevation	0.11549	34.205	0.001
Slope gradient	– 0.28621	17.289	0.001
Distance to road	0.00721	9.749	0.002
Radiation index	0.00001	4.390	0.036
Intercept	– 10.50349	4.398	0.036

N = 234, Chi-square = 149.230, Probability < 0.001, Pseudo R-square (Cox and Snell = 0.527 and Nagelkerke = 0.703), Percent correct prediction = 85%

probability map within the geographic constraints of the study area.

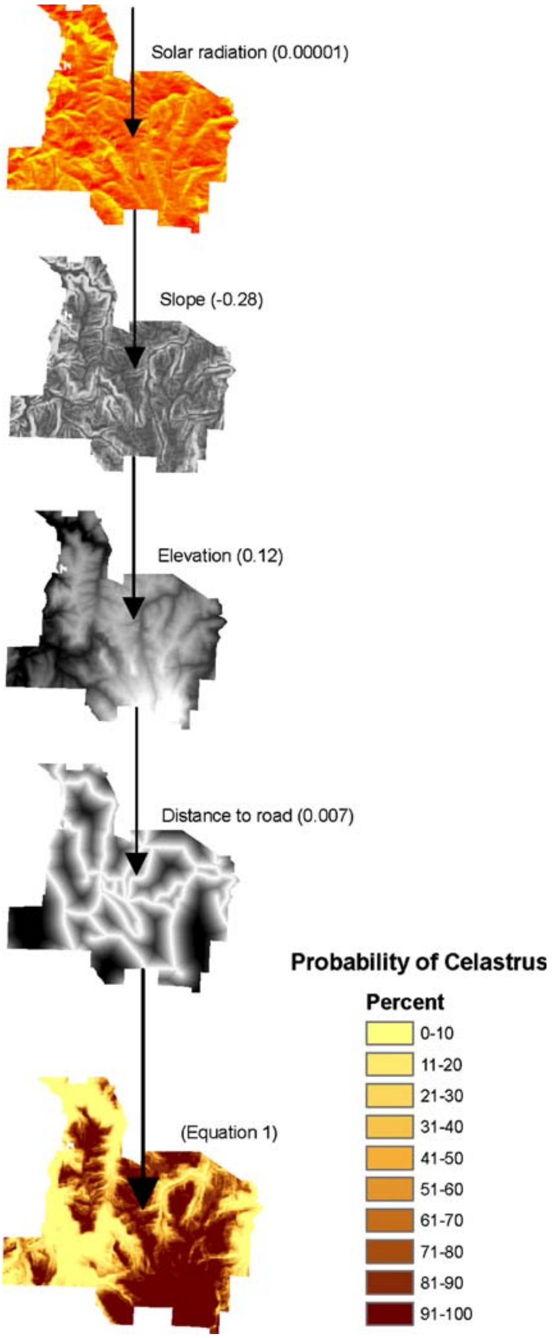


Fig. 2 Schematic of procedure followed to generate probability surface map for predicting *C. orbiculatus*. Because the predicted probability is calculated for each raster cell, only predictor variables represented in raster format can be employed. Logit model coefficients appear in parentheses next to each raster

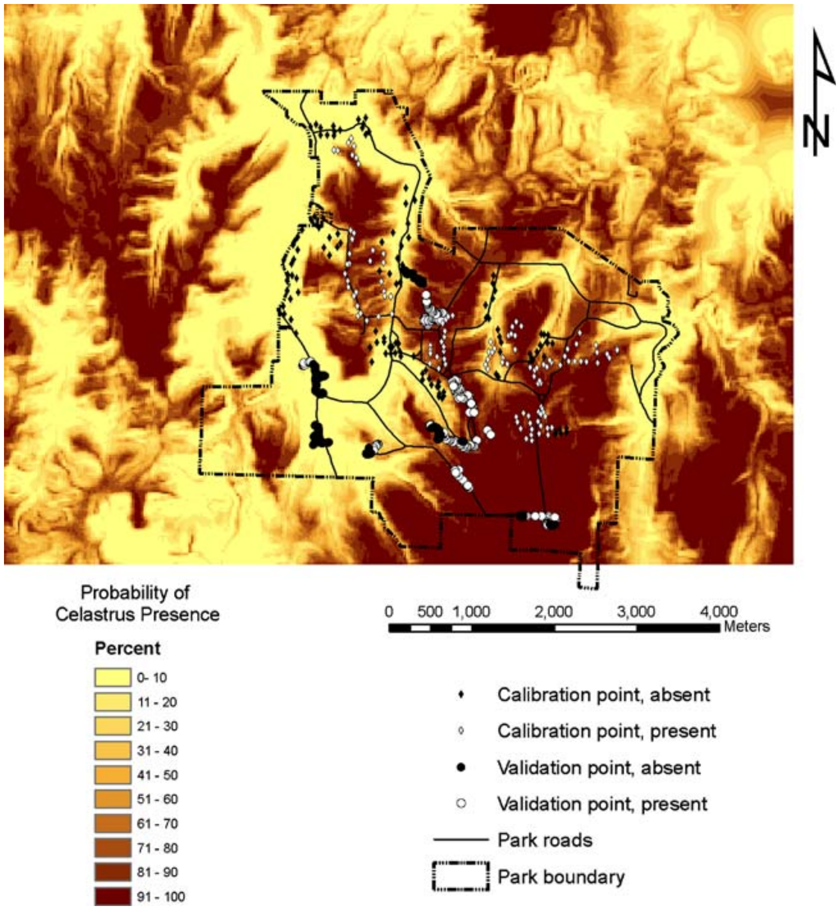
Discussion

In our study, *C. orbiculatus* was significantly associated with higher elevation, which in turn was associated with gentle slopes on interfluves. It was also slightly more likely to occur at a distance from roads and in areas with higher radiation indices. Because accurate mapping is a problem of spatial prediction rather than ecological explanation, in generating a probability map of *C. orbiculatus* occurrence, we use these associations in a purely predictive context. One advantage of this is that multicolinearity, a difficult problem in an explanatory context, is a less significant issue when the purpose of the regression model is simply to predict the value of the dependent variable (Rawlings 1988). Because these predictor variables are readily calculated from a digital elevation model or can be easily converted from vector to raster formats from a road map, it is possible to extrapolate the value of each predictor variable across a wide geographic area. Digital elevation models and road maps for the US and other geographic areas can be downloaded at no cost from publicly available sources. By applying the parameters of the logistic regression shown in Table 4, a raster data layer of the probability of occurrence of *C. orbiculatus* is constructed in a straight-forward manner using standard GIS software (ArcGIS 9.0) (ESRI 2005). Given these conditions of high data and software availability, logistic regression models can form the basis of probability of occurrence maps for invasive plants over broad geographic areas. In this lies the methodological potential of map algebra for the study of invasive plants and also potentially less mobile invasive animals (e.g., zebra mussels). However, it is important to also indicate the limits to this kind of spatial extrapolation. These limits are determined by three primary factors: the extent to which the species has invaded all suitable habitats (dispersal limits), the population that the sample represents, and the stability of causal relationships between predictor variables and the invasive plant.

Dispersal limits

Birds are considered important dispersers of *C. orbiculatus* seed. Baird (1980) found

Fig. 3 Probability of *C. orbiculatus* occurring in all sites in and near Giant City State Park. Results are derived from map algebra using logistic regression over a raster grid. Calibration and validation sites with and without *C. orbiculatus* are shown for comparison with predicted probabilities

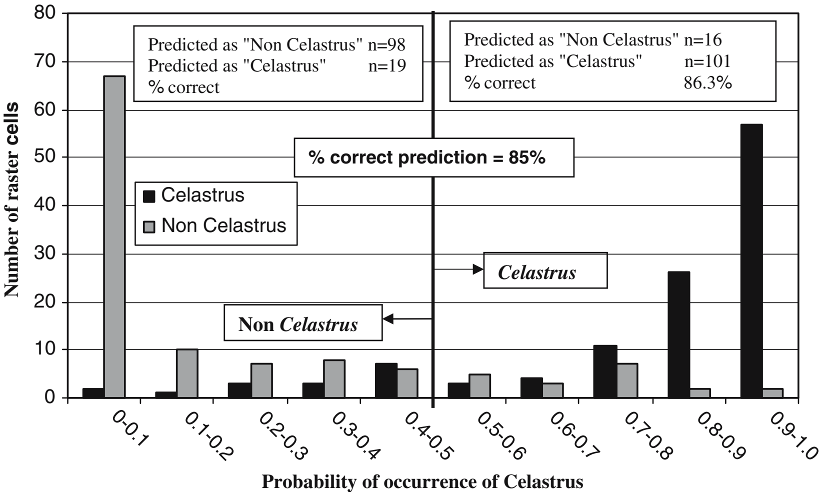


C. orbiculatus predated by frugivorous winter resident birds. Hoppes (1988) discovered a spatial pattern of bird-dispersed fruits and seeds in a woodland in Illinois, where seed density declined with distance from seed source and highest proportion of seeds were dispersed from gap to gap, rather than from gap to woodland interior. Seed occurrence decreased with increasing distance from canopy gap. Greenberg et al. (2001) found *C. orbiculatus* fruits defleshed by birds had highest germination rates. Ellsworth et al. (2004) determined that *C. orbiculatus* does not persist in the seed bank, but seedling recruitment is from current year seed fall. Given these dispersal dynamics, it is possible that *C. orbiculatus* is not present in areas of Giant City Park that may actually be suitable for its growth due to lack of facilitating dispersal. If the sites used to calibrate and validate the logistic regression model were taken from a well-seeded area, then the resulting map would predict the occurrence of *C. orbiculatus* in areas that are suitable, but to which it may not have yet been dispersed. These would constitute sites of potential invasion rather than present occurrence.

Sample representativeness

Because the focus area of this study was Giant City Park, calibration and validation samples were drawn from within Park boundaries and are representative of the park's environments. Fig. 3 shows an extrapolation of the probability map beyond the park's boundary to include the entire quadrangle from which a digital elevation model was used to derive predictor variables. Given the similar topographic, geologic and climatic conditions within and adjacent to the park, this is likely valid, but only to the extent that the calibration and validation samples are representative of the quadrangle as well as of the park.

Fig. 4 Frequency distribution of probabilities of *C. orbiculatus* occurring in raster cells estimated using raster-based logistic regression. Correct and incorrect predictions are shown for each probability level. Note that few cells contain probabilities close to 0.5 indicating that the prediction equation is robust and that invaded and non-invaded sites are distinct



With these considerations, it is possible to use map algebra to derive probability maps of invasive plants for mesoscale landscapes, provided the calibration and validation samples are designed to be representative of the areas to which the extrapolation is to be applied, and the logistic regression models derived from those samples have high predictive power in validation.

The stability of causal relationships

While the logistic regression upon which map algebra was based was highly predictive, the most significant variables—elevation and slope—do not have a direct effect on environmental suitability for *C. orbiculatus*, but influence its occurrence through other factors (Fig. 5). Introduction of *C. orbiculatus* in Giant City Park is linked to agricultural homesteads located on flat interfluves (pers. comm. Skufca). Within and adjacent to Giant City Park, abandoned farm fields and home sites occurred most often on higher flat areas where more fertile soils and favorable cultivation and construction conditions were available compared to narrow, steep unglaciated valleys. Upon purchase by the State of Illinois beginning in 1927, these areas have undergone successional change in vegetation and in some cases have been regularly disturbed through wildlife and recreation management practices. Steep valleys, however, were never farmed but were timbered in the 19th and 20th centuries, and likely underwent successional growth prior to the introduction of *C. orbiculatus* in the area. These late-successional forest types dominated by oak generally do not contain *C. orbiculatus*. These land use and disturbance patterns can be hypothesized to be major factors in the invasion pattern and establishment of *C. orbiculatus* within and adjacent to Giant City Park. Disturbance, and consequent change in community structure and composition that characterize succession, hasten invasion and establishment of non-native species (Rejmanek and Richardson 1996) including *C. orbiculatus*.

Table 5 Validation of map algebra logistic regression model based on 196 sites with and 242 sites without *C. orbiculatus* collected in Giant City State Park in June, 2005

Observed		Predicted		
		Presence/absence		Percentage correct
		Yes	No	
Presence/absence	Yes = 196	173	23	88.3%
	No = 242	35	207	85.5%
Overall percentage		208	230	86.9%

The model correctly predicted 86.9% of sites

Celastrus orbiculatus may, therefore, not be associated with high elevation and gentle slopes in other geographic locations that do not share a similar land use history. In other landscapes with different land use histories and topographic

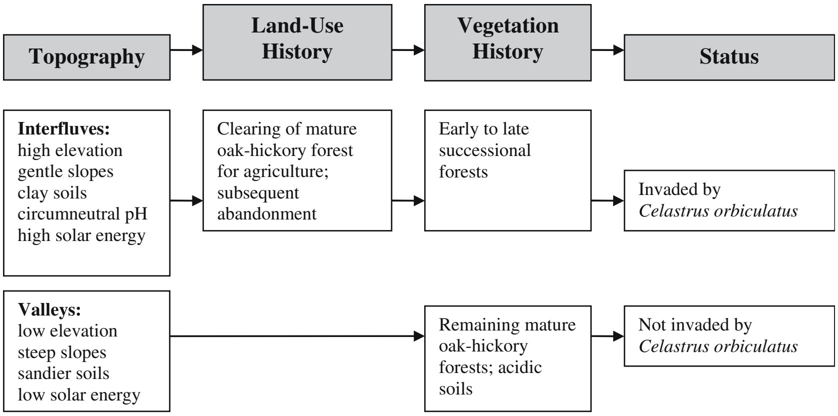


Fig. 5 Landscape-level relationships between topography, land use, disturbance regimes and *C. orbiculatus*

structures, *C. orbiculatus* could be associated with low elevations or with steep slopes reflecting disturbance regimes and successional stage in those landscapes. The predictive accuracy of the probability map, therefore, declines with the strength of the association between causal and the merely correlated variables upon which it is based.

Conclusions

Map algebra using logistic regression was found to provide a powerful means of extrapolating the occurrence of *C. orbiculatus* across the Southern Illinois study area and beyond to similar neighboring environments for which the field samples are representative. For this reason alone it provides an important analytical tool in identifying locations where invasive plant species do or may occur and, if combined with spatial analyses incorporating distribution mechanisms, where invasive plants are likely to spread. These techniques should therefore be useful to managers in controlling invasive species.

The use of map algebra for accurately mapping the occurrence of invasive plants requires that variables that are representable in raster-based form are highly predictive of its location. The increasing availability of digital elevation models and remote sensing data in raster form, and other geographic information system-relevant data in vector form that are convertible to raster, makes meeting this requirement increasingly possible for many invasive species. However, the elimination of all non-raster variables always results in some loss of predictive power.

Nevertheless, while the power of map algebra lies in spatial extrapolation, three factors control the accuracy of probability maps extrapolated from regression analysis across raster data layers: dispersion dynamics, representativeness of the sample to the extrapolation population, and the stability of causal relationships. In this case, the application of map algebra to a logistic regression using variables that have direct effects on *C. orbiculatus*—disturbance, successional stage—would likely yield a probability map that maintains its validity extrapolated over a larger area, but could only be created if these direct effects can be captured in raster form.

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