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Article

Invasion of Eastern Texas Forestlands by Chinese Privet: Efficacy of Alternative Management Strategies

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Abstract: Chinese privet (*Ligustrum sinense*) was the most prevalent invasive shrub in the forestlands of Eastern Texas in 2006. We analyzed extensive field data collected by the Forest Inventory and Analysis Program of the U.S. Forest Service to quantify the range expansion of Chinese privet from 2006 to 2011. Our results indicated the presence of Chinese privet on sampled plots increased during this period. Chinese privet spread extensively in the north. Results of logistic regression, which classified 73% of the field plots correctly with regard to species presence and absence, indicated probability of invasion was correlated positively with elevation, adjacency (within 300 m) to water bodies, and site productivity, and was correlated negatively with stand age, site preparation (including clearing, slash burning, chopping, disking, bedding, and other practices clearly intended to prepare a site for regeneration), artificial regeneration (which refers to planting or direct seeding that results in at least 50% of the stand being comprised of stocked trees), and distance to the nearest road. Habitats most at risk to further invasion (likelihood of invasion > 40%) under current conditions occurred primarily in Northeast Texas. Practicing site preparation and artificial regeneration reduced the estimated probabilities of further invasion.

Keywords: biodiversity; biological invasions; invasive species; multiple logistic regression; probability of invasion

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1. Introduction

Chinese privet (*Ligustrum sinense* Lour) was the most aggressive invasive shrub in the forestlands of Eastern Texas in 2006 [1] and appeared on the Texas Department of Agriculture's list of nuisance plants [2]. Chinese privet is native to Southeast Asia, south of China, east of India, and north of Australia, and was introduced into the U.S. in the mid 1800s as an ornamental shrub [2]. It occurs from Virginia south to Florida and west to Kentucky, Missouri, Oklahoma, and Texas. It also occurs in the Atlantic coastal states as far north as Massachusetts [1,3].

The greatest threat posed by Chinese privet is large-scale ecosystem modification. Because of its shade tolerance and abundant regeneration, it is capable of flourishing under dense forest canopies and limiting the regeneration of native trees [4], native plant communities [5,6], pollinators [7], wildlife such as songbirds [6], earthworms [8], and beetles [9], as well as recreational activities [5]. Land-management agencies are particularly alarmed by the abundance of privet in natural bottomland hardwood stands and their competitive exclusion of seedlings of native bottomland hardwood species [10]. Chinese privet is a perennial shade-tolerant shrub or small tree which can grow to a height of nine meters, with multiple stems and leaning-to-arching long leafy branches [11]. It matures rapidly, producing viable seeds and also reproducing vegetatively by means of root suckers. It contains phenolic compounds to defend against herbivores [2] and can form dense thickets, invading disturbed sites and fencerows in both bottomland and upland forests in the Southern U.S. [11,12]. Although it prefers wet, damp conditions, it is able to live in a variety of habitats and soil conditions [2]. It grows most rapidly in habitats with abundant sunlight, but also readily invades shady forests, especially in stream floodplains [4]. Chinese privet seeds germinate immediately without cold stratification [13] and are spread widely by songbirds, white-tailed deer (*Odocoileus virginianus*), white-footed mice (*Peromyscus leucopus*), and golden mice (*Ochrotomys nuttalli*) [6,11,14,15].

Among the prerequisites for the development of effective management strategies to control non-native plant invasions are the quantification of range expansion trends and the identification of the factors, including management activities, affecting the probability of invasion [17]. Current forest management activities include site preparation, such as clearing, slash burning, chopping, disking, bedding, and other practices clearly intended to prepare a site for regeneration, followed by artificial regeneration, which usually refers to planting or direct seeding that results in at least 50% of the stand being comprised of stocked trees, or natural regeneration, which usually refers to a situation in which the stand is comprised of at least 50% previously existing and/or naturally seeded trees [16]. In the present study, we first analyzed an extensive dataset from the Forest Inventory and Analysis (FIA) program of the U.S. Forest Service [1] to identify areas within the forestlands of Eastern Texas that were invaded by Chinese privet from 2006 to 2011. We then quantitatively identified a set of landscape conditions, forest features, forest management activities, and disturbances as potential factors affecting the probability of invasion. Finally, based on the most influential factors, we predicted the probabilities of future invasions under different assumptions regarding the percentage of all forest plots (25%, 50%, 75%, or 100%) that had received either site preparation or artificial regeneration.

2. Methods

2.1. Study Area and Data Sources

The study area is Eastern Texas, one of the highest timber production areas in the country [18], which has been invaded by Chinese privet [19]. The average annual temperature in Eastern Texas is 19.5 °C, with an average of 240 frost-free days per year, and average annual precipitation is around 132 cm, which usually is well distributed throughout the year [20].

We obtained data on the presence and absence of Chinese privet from the Southern Nonnative Invasive Plant data Extraction Tool (SNIPET) of the U.S. Forest Service [1]. We obtained data on landscape features, forest conditions, forest management activities, and disturbances from the FIA Data and Tools data set [21]. The FIA program is a forest inventory program in which each state inventory is reported every five years [22]. The SNIPET and the FIA Data and Tools provide access to field data that have been collected from a lattice of 4047-m^2 hexagons, with one sample plot located randomly within each hexagon [22]. Each sample plot consists of four subplots of radius 7.32 m which form a cluster consisting of a central subplot and three peripheral subplots equidistant from each other arrayed in a circle of radius 36.58 m centered on the central plot [22]. On each subplot, inventory crews of the Southern Research Station estimate percent cover by target invasive species [23] and also record a suite of landscape features, forest conditions, forest management activities, and disturbances that have occurred [16]. The inventory crews survey a portion of the subplots within a state each month throughout the year, and, upon completing a five-year cycle, repeat the subplot surveys in the same order during the next five-year cycle, thus consecutive samples on any given subplot occur at approximately the same time of year [21].

2.2. Quantification Spread

We quantified Spread by noting the presence (with cover) or absence (without cover) of Chinese privet on each subplot sampled during each of these two inventories in 2006 and 2011 [1] and then mapping and counting the plots in each inventory with Chinese privet present.

2.3. Identification of Invasion Determinants

To quantitatively identify potential factors affecting the probability of invasion, we examined a set of landscape conditions, forest features, forest management activities, and disturbances (Table 1). Landscape conditions included elevation, slope, and adjacency to water bodies within 300 m. Forest features included stand age and site productivity. Forest management activities included (1) site preparation (clearing, slash burning, chopping, disking, bedding, or other practices clearly intended to prepare a site for regeneration); (2) artificial regeneration (planting or direct seeding resulting in at least 50% stocked with live trees of any size); and (3) natural regeneration (growth of existing trees, natural seeding, or both, resulting in a stand at least 50% stocked with live trees of any size). Disturbances included (1) distance between the plot and the nearest road; (2) fire disturbance (from crown or ground fire, either prescribed or natural); (3) animal disturbance (from beaver, porcupine, deer/ungulate, rabbit, or a combination of animals); and (4) wind disturbance (including, but not limited to, damages from hurricanes and tornados).

Table 1. Descriptions, values or units of measure, and means or frequencies of climatic conditions, landscape features, forest conditions, and management activities and disturbances evaluated as potential factors of site invasion by Chinese privet in forest plots of Eastern Texas.

Variable	Value or Unit of Measure	Mean (Range) or Frequency
Landscape conditions		
Elevation	m	259.36 (−79 ~ 999)
Slope	degree	2.07 (0 ~ 32.5)
Adjacency to water bodies within 300 m	0: no 1:yes	0: 1924 1: 473
Forest features		
Stand age	year	35.73 (1 ~ 104)
Site productivity	1: 0–1.39 2: 1.40–3.49 3: 3.50–5.94 4: 5.95–8.39 5: 8.40–11.54 6: 11.55–15.74 7: >15.74 $m^3ha^{-1}year^{-1}$	1: 9 2: 154 3: 661 4: 933 5: 541 6: 95 7: 4
Forest management activities		
Site preparation [a]	0: no 1:yes	0: 2312 1: 85
Artificial regeneration [a]	0: no 1:yes	0: 1712 1: 685
Natural regeneration [a]	0: no 1:yes	0: 2351 1: 46
Disturbances		
Distance to the nearest road	1: <30 2: 30–91 3: 92–152 4: 153–305 5: 306–805 6: 806–1609 7: 1610–4828 8: 4829–8047 9: >8047 m	1: 179 2: 394 3: 283 4: 508 5: 685 6: 253 7: 72 8: 13 9: 10
Fire disturbance [a,b]	0: no 1:yes	0: 2381 1: 16
Animal disturbance [a,b]	0: no 1:yes	0: 2384 1: 13
Wind disturbance [a,b]	0: no 1:yes	0: 2329 1: 68

[a]: Normally within the past 5 years; [b]: A disturbance code of 1 indicates at least 25% of the trees in a stand are damaged.

We associated the data on presence and absence of Chinese privet (SNIPET) with the data on landscape features, forest conditions, forest management activities, and disturbances (FIA Data and Tools) using the FIA plot identification numbers. We then examined all potential factors via logistic regression using a backward elimination procedure [24] in SAS 9.2 (SAS Institute Inc., Cary, NC, USA). When we ran the logistic regression, we eliminated insignificant variables and re-estimated the model until the Akaike information criterion (AIC) reached the minimum score [25]. We then used Hosmer-Lemeshow's test to check the goodness-of-fit of the model [26]. Finally, we used the area under the receiver operating curve (AUC) to examine the reliability and validity of our model [26].

2.4. Probabilities of Further Invasion

First, based on the regression results, we estimated the probability of presence of Chinese privet on each plot (π). We then explored the effects of each of the two alternative management strategies by randomly choosing 25%, 50%, 75%, or 100% of the plots and assigning a "1" to (1) the site preparation variable or (2) the artificial regeneration variable associated with the chosen plots. Finally, we superimposed the probabilities of presence under each scenario on a map of the study area using ArcMap^{TM} 10.2.1 (ESRI, Redlands, CA, USA).

3. Results

Chinese privet spread extensively in the north through Eastern Texas from 2006 to 2011, with the species exhibiting a few hot-spots in the south (Figure 1). The presence of Chinese privet on sampled plots more than doubled, from 102 plots (4.26% of all plots) to 272 plots (11.34%), from 2006 to 2011. The number of counties invaded increased from 15 in 2006 to 41 in 2011, leaving only two counties un-invaded. The range expansion occurred mainly in the north, but invasion intensities increased noticeably in Jefferson, Walker, Tyler, and San Jacinto counties. Bowie county had the largest number of plots invaded (19 plots) in 2006, while Cass county had the largest number of plots invaded (23 plots) in 2011.

Results of logistic regression indicated a positive correlation between the likelihood of invasion and elevation, adjacency (within 300 m) to water bodies, and site productivity, and a negative correlation between likelihood of invasion and stand age, site preparation, artificial regeneration, and distance to the nearest road (Table 2). The model classified 73% of the total number of plots correctly with regard to presence and absence of Chinese privet (based on a cut-off criterion of $\pi = 0.14$). Hosmer and Lemeshow's goodness-of-fit tests indicated no significant difference ($P = 0.97$) at the 5% significance level between observed and model-predicted occupancy values. The AUC (0.76) indicated the model was "good".

Figure 1. Presence (brown dots) and absence (green dots) of Chinese privet in plots sampled in Eastern Texas in (**a**) 2006 and (**b**) 2011 as part of the Forest Inventory and Analysis Program of the U.S. Forest Service [1].

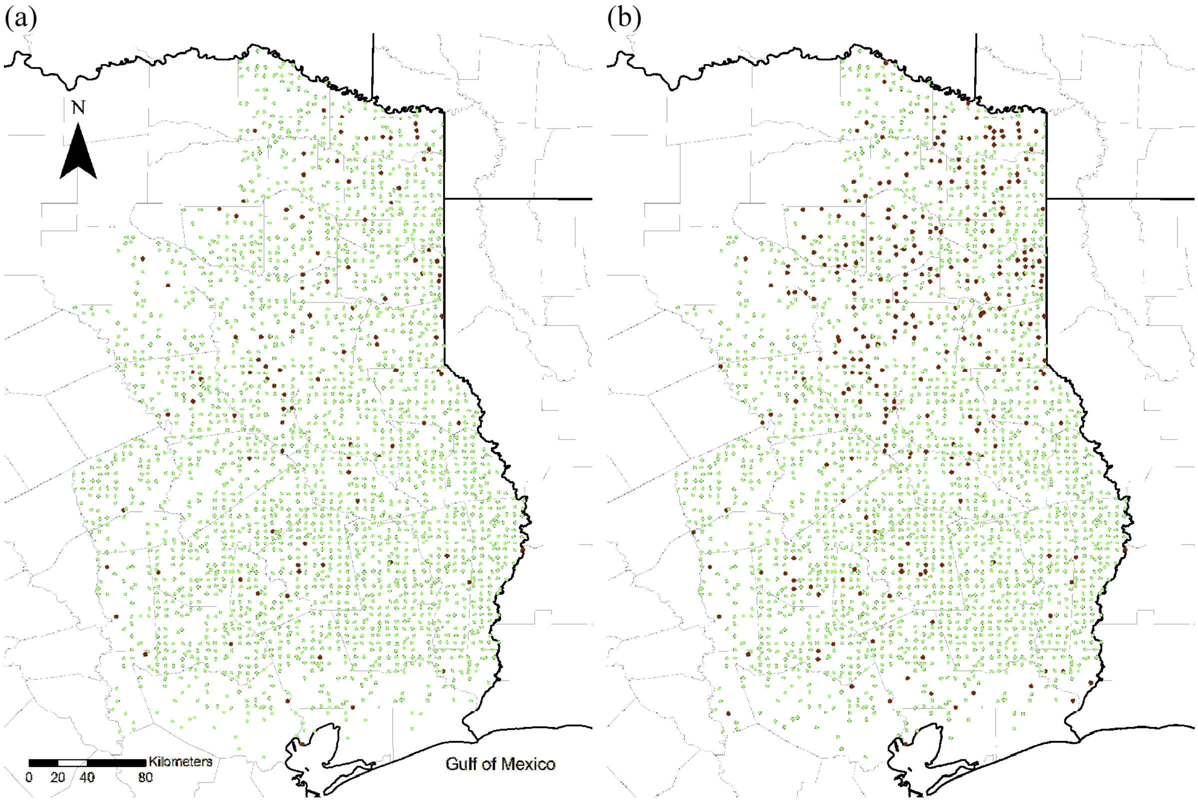


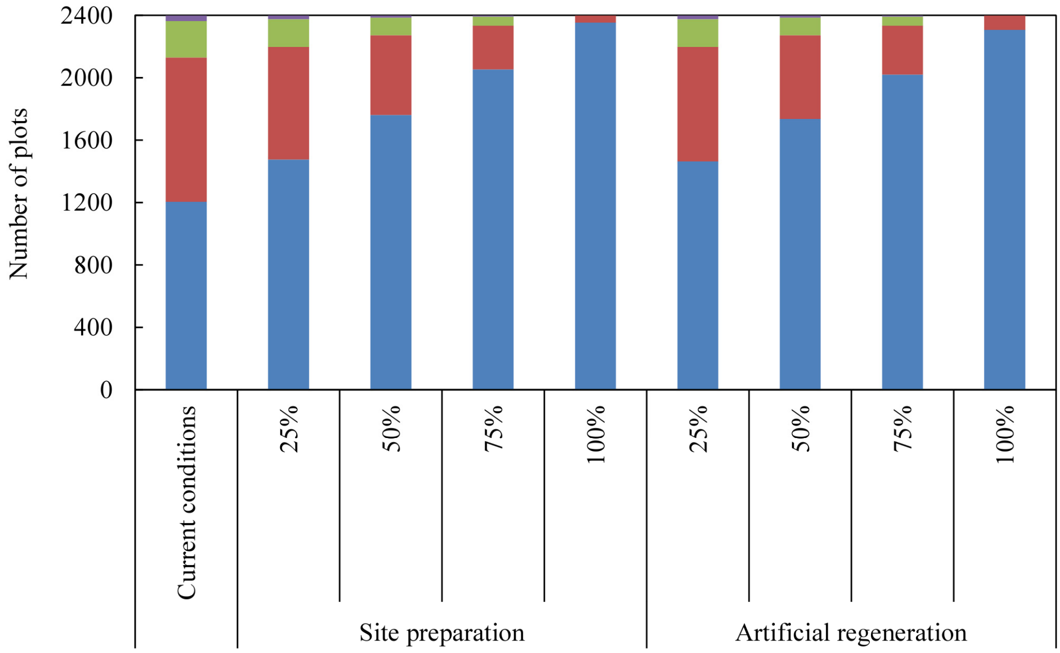
Table 2. Potential determinants of Chinese privet invasions of forested plots in Eastern Texas as indicated by results of stepwise multiple logistic regression.

Variable	Estimated Coefficient	Estimated Standard Error [a]	Estimated Odds Ratio [b]
Landscape conditions			
Elevation	0.0023	0.0006	1.0023
Adjacency to water bodies within 300 m	0.4746	0.1675	1.6073
Forest features			
Stand age	−0.0179	0.0037	0.9823
Site productivity	0.3144	0.0747	1.3694
Forest management activities			
Site preparation	−0.8501	0.3916	0.4273
Artificial regeneration	−0.6436	0.1732	0.5254
Disturbances			
Distance to the nearest road	−0.1306	0.0436	0.8776
Constant	1.7972	0.8683	—

[a]: p-value < 0.05; [b]: The estimated odds ratio indicates the change in the probability of invasion by Chinese privet that would result from a 1-unit change in the value of the indicated variable. For example, a 1-uint change, from 0 (no) to 1 (yes), in site preparation indicates that Chinese privet invasion is 0.4273 times less likely than before, after controlling for the other variables.

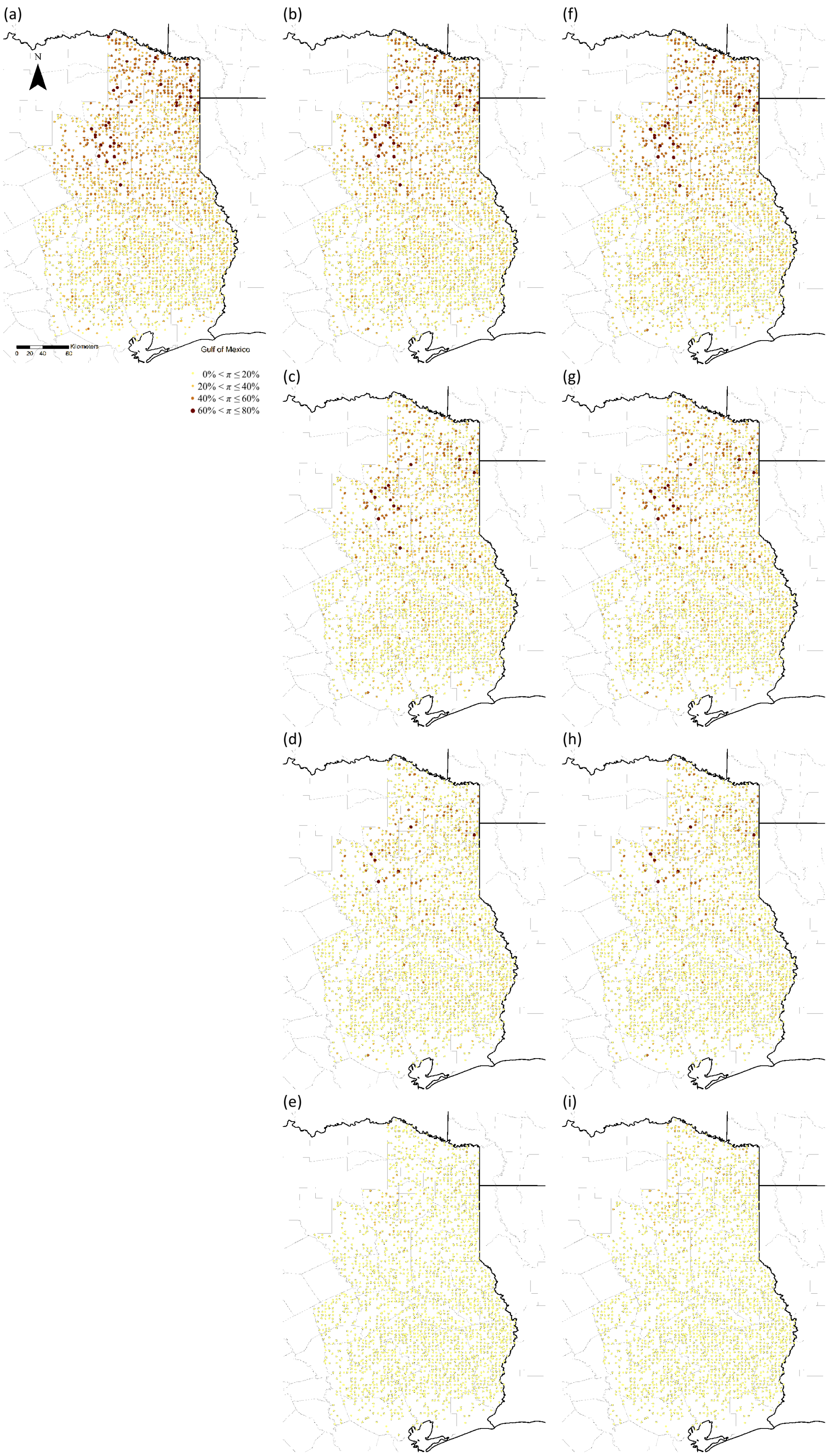
Estimated probabilities (π) of further invasion under current conditions indicated that approximately 50% of the plots fell within the $0 < \pi \leq 0.2$ category, 39% within the $0.2 < \pi \leq 0.4$ category, 10% within the $0.4 < \pi \leq 0.6$ category, and about 1% within the $0.6 < \pi \leq 0.8$ category (Figure 2). The majority of the relatively higher estimated probabilities ($\pi > 0.4$) were located in Northeastern Texas (Figure 3a).

Figure 2. Number of plots within the indicated categories of estimated probability (π) of further invasion (blue: $0 < \pi \leq 0.2$, red: $0.2 < \pi \leq 0.4$, green: $0.4 < \pi \leq 0.6$, purple: $0.6 < \pi \leq 0.8$) by Chinese privet assuming current conditions, site preparation on 25%, 50%, 75%, or 100% of the plots (chosen at random), and artificial regeneration on 25%, 50%, 75%, or 100% of the plots.



Estimated probabilities of further invasion were reduced the most by site preparation, followed by artificial regeneration (Figure 2). The different levels, 25%, 50%, 75%, and 100%, of site preparation decreased the overall π values from 0.23 to 0.19, 0.14, 0.10, and 0.05, respectively, and decreased the number of plots with $\pi > 0.2$ from 1193 to 922, 637, 345, and 44, respectively. The different levels of artificial regeneration decreased the overall π values from 0.23 to 0.19, 0.15, 0.11, and 0.07, respectively, and decreased the number of plots with $\pi > 0.2$ from 1193 to 934, 661, 377, and 90, respectively. Once again, whether assuming site preparation (Figure 3b–e) or artificial regeneration (Figure 3f–i), the majority of the relatively higher estimated probabilities ($\pi > 0.2$) were located in Northeastern Texas.

Figure 3. Estimated probabilities of further invasion by Chinese privet in plots sampled in Eastern Texas as part of the Forest Inventory and Analysis Program of the U.S. Forest Service assuming (**a**) current conditions; (**b**) site preparation on 25%; (**c**) 50%, (**d**) 75%; or (**e**) 100% of the plots (chosen at random); and (**f**) artificial regeneration on 25%; (**g**) 50%; (**h**) 75%; or (**i**) 100% of the plots.



4. Discussion

Wang and Grant estimated probabilities of invasion of Chinese privet within southern US forestlands by correlating landscape features, climatic conditions, forest conditions, and management activities and disturbances with presence or absence of privet based primarily on analysis of data collected during the FIA inventory period that ended in 2006 [19]. Their study identified areas vulnerable to invasion throughout Mississippi, with a band stretching eastward across South-Central Alabama, and also areas in Western Louisiana and Eastern Texas. The spatial pattern of our results is in general agreement with their projection of Chinese privet distribution in Eastern Texas. However, our results based on analyzing data collected during the FIA inventory period that ended in 2011 suggest that their model may have underestimated the probability of further invasion (π = 0.15 compared to π = 0.23 in the present study).

The potential effect of landscape conditions on Chinese privet invasions is suggested by a positive correlation of invasions with elevation and adjacency to water bodies. About 45% of existing invasions into Eastern Texas forestlands have occurred at elevations between 100 and 195 m where favorable landscapes are created on well-drained sites [27]. Adjacency to water bodies also appears to favor Chinese privet invasion. Hanula *et al.* found Chinese privet heavily infested streamside forests along the Oconee River north of Athens, GA [5]. Merriam found Chinese privet had a coefficient of association more than 50% higher for river and stream banks in North Carolina than would be expected if its distribution among different edge types was random or uniform [28]. This suggests that moist riparian soils provide suitable conditions and/or floods might be a seed-carrying mechanism for the seeds [6,28].

Certain forest features appear to facilitate invasions. More than 50% of the existing invasions into Eastern Texas forestlands have occurred in stands < 30 years old. Swarbrick *at el.* indicated that Chinese privet can germinate and establish under very low light conditions (1%–5% full sunlight), but cannot survive more than a few years unless the canopy is broken. This would suggest that Chinese privet can invade relatively younger forest stands with more canopy gaps and higher light availability. In addition, high site productivity appears to favor Chinese privet invasions. Logically, high productivity sites provide favorable conditions for native and invasive species alike [19], however, being evergreen likely provides an extra advantage to Chinese privet since it can photosynthesize throughout the winter when there is no hardwood canopy cover [5].

Of the forest management activities we explored, increased management efforts on site preparation and/or artificial regeneration, decreased the likelihood of Chinese privet invasions dramatically. Although practicing site preparation and/or artificial regeneration may be neither feasible nor desirable, our results emphasize the opportunity for reducing the likelihood of invasions in areas at high risk, given the potential economic losses associated with Chinese privet invasion. For example, Stone (1997) has shown that practicing site preparation procedures such as hand-pulling seedlings and mowing and/or cutting stems larger than 2.5 m can successfully reduce Chinese privet invasion in relatively small areas, such as nature preserves [29]. Chinese privet has been shown to inhibit reproduction and growth of trees through altering the occurrence of arbuscular mycorrhizal fungi in the resident soil [30] and influencing a number of key nutrient cycling processes [31]. In addition, a combination of shading and some allelopathic effect of adult leaf leachate inhibit the growth of other plants under a canopy of Chinese privet and contribute to a reduction in plant diversity after invasion [32]. These negative effects manifest themselves as lost profits in forests managed for timber [33]. Moreover, extensive and oftentimes cost-prohibitive measures are required to eradicate Chinese privet once established. With artificial regeneration following timber harvest, stands are intensively managed for desired species, which maintain conditions that are more appropriate for the native desired species and less appropriate for Chinese privet [34]. This usually includes site preparation through clearing, root-raking, slash burning, chopping, disking, and/or bedding [16,22,35], which reduces the likelihood of Chinese privet establishment into the newly created forest gap. This removal of non-desirable species and subsequent rapid stand growth can inhibit the invasion establishment into a newly formed forest gap [36], which is otherwise at risk for invasion given the aggressive exploitation of light gaps and rapid growth under high light conditions exhibited by Chinese privet [5,7,9]. Planting native species and subsequent management for those species reduces the opportunity for Chinese privet spread.

As for the disturbance effects, the likelihood of invasion increased significantly as the distance to the nearest road decreased. Chinese privet commonly is found adjacent to roadways [28]. Flory and Clay found that roads could increase soil moisture, soil disturbance, nutrient runoff, sun exposure, and temperature, which can promote plant invasions independent of roads [37]. The successional status of Chinese privet is unclear, but it appears that sun exposure is an important component for the establishment [38] and roads provide this essential component.

While species distribution models such as ours are useful for determining invasion potential for large areas, there are some shortcomings of this modeling approach. First, one cannot rule out possible biases in data resulting from the details of the field sampling and the life history of the species. In our study, the presence data doubled and the number of invaded counties increased from 15 to 41 in five years, which seems quite rapid for a shrub. Hence, we might reasonably hypothesize that small Chinese privet seedlings might have been present but unnoticed by inventory crews in 2006, and first noticed as taller adult shrubs in 2011. However, Chinese privet does have the potential to disperse long distances via seed dispersal by songbirds [6,39]. Although not documented for Chinese privet, seed dispersal by birds has been estimated at around 1000 m [40] and 1200 m [41] for Chinese tallow (*Triadica sebifera* (L.) Small) in North Carolina and Texas, respectively, and around 5 km to 10 km for swamp privet (*Forestiera acuminate* (Michx.) Poir.) in Mississippi [42]. A second shortcoming is that our model might not represent the entire potential niche of the species because invasion is an ongoing process [43]. In future work, it would be interesting develop methodologies that could combine quantitatively species distribution time series data with potentially changing species demographic traits to project possible invasion scenarios.

In conclusion, our analyses suggest that range expansion by Chinese privet probably will continue to threaten the forestlands in Eastern Texas, particularly in the north. However, the opportunity exists for decreasing the probability of invasion via increased practice of selected management activities. In addition, by identifying the determinants of Chinese privet invasion and potential habitats, our analyses should provide land managers and restoration practitioners with useful information to plan proactive management strategies for the areas most likely to be invaded.

Author Contributions

This study was designed and conducted by Hsiao-Hsuan Wang and William E. Grant. H.-H. Wang organized the data and conducted statistical analyses. H.-H. Wang and W.E. Grant led the writing.

Conflicts of Interest

The authors declare no conflict of interest.

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