Development and Validation of Ecological Site Quality Model: An Example of Chamaecyparis formosensis in Taiwan

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ABSTRACT

An ecological site quality model was developed to aid in predicting the suitability of new locations for growing tree species. This model uses environmental variables to evaluate potential productivity. Data was input into a geographic information system, including 3rd Forest Resources and Land Use Inventory of Taiwan by integrated data from the climate data of the Central Weather Bureau of Taiwan, the Taiwan Forest Bureau, the Council of Agriculture in Taiwan, and the United States Naval Observatory to model the distributions of elevation, slope, aspect, solar radiation, rainfall, evapotranspiration, temperature, and soil nitrogen within Taiwan. Ecological requirements of Chamaecyparis formosensis were derived from the literature and from 211 ground survey plots. Using 22,501,993 40 m × 40 m grids within Taiwan, we modeled the requirements of C. formosensis for solar radiation, temperature, evapotranspiration, soil moisture, and soil nitrogen. We tested the model by comparing predicted sites to its known distribution of C. formosensis in Taiwan. All of the known locations of C. formosensis fell within the area predicted by the model and about 63.91% of the ecological site quality (ESQ) values were above 0.6. It showed that the model is good for evaluating the site quality for the tree species.

Keyword: Chamaecyparis formosensis, geographic information systems, GIS, individual response function, species distribution, site quality

INTRODUCTION

The Red Cedar, Chamaecyparis formosensis, is an endemic species of Taiwan. A dominant species in Taiwan’s temperate coniferous forests (Horng et al., 2000), it is found between 1,000 m–2,600 m in elevation (Wang, 1968). It can reach a height of 50 m and a diameter of 300 cm (Wang, 1968). It is a large, slow-growing tree (Kuo, 1995) with an excellent longevity beyond 2,000 years, as recorded by Wang (1968). Because of its great size and the durability of its rot resistant wood (Wang, 1968), it was in great demand. Since 1912, this tree species was harvested so intensively that it was in danger of extinction (Lee, 1962; Horng et al., 2000). Almost 57% of the estimated 102,000 ha–112,000 ha original forest of C. formosensis, and its congeneric C. obtusa var. formosana, was logged (Horng et al., 2000). Apart from the cease of C. formosensis in 1989, also there is an ongoing effort to plant new stands and to regenerate the forests (Horng et al., 2000). About half of this forest has since been replanted. Much of its range is now protected by national parks and nature reserves (Horng et al., 2000). Since historical records are limited (Horng et al., 2000), however, there is some difficulty in identifying suitable places in which to plant new stands.

The site index model is useful to estimate the quality of various stands of a given species of tree (Clutter et al., 1983). Since this method relies on detailed information from the trees in the stand, it requires current or previous existence of a particular tree species within the stand (Clutter et al., 1983). This means that the site index model cannot be used to assess a site in which to grow a new tree species.

Botkin (1993) developed an individual response function that combines the environmental variables (light, temperature, drought, and nitrogen) of a stand with the maximum basal area of a tree species to classify the quality of the stand for the tree species. By requiring information on the basal area, the applicability of Botkin’s model is also limited for sites...
in which the tree species is already established. The advantage of Botkin’s model, as compared to the site index model, is that it also uses environmental variables.

Often, however, reforestation requires planting of trees in new locations. To guarantee survivability of these trees and to conserve effort, it is important to evaluate the suitability of the new locations of reforestation. Furthermore, due to the wide fluctuations of environmental conditions over time, Botkin’s (1993) environmental variables are adequate to predict current and future habitat suitable for a particular tree species. Therefore, we eliminated the per-plot maximum basal area from Botkin’s (1993) individual response function to form the ecological site quality model (ESQ). We tested ESQ by identifying the locations within Taiwan with ecological conditions similar to those required by C. formosensis. We then compared these locations to those known to contain natural populations of C. formosensis.

METHODS

Taiwan Survey

Taiwan is a sub-tropical island (121.5˚E and 23.1˚N) with high mountains over 3800 m in elevation. Through the even division of Taiwan into grids 40 m × 40 m, a digital elevation model of Taiwan was developed from aerial photographs from a survey of Taiwan in 1987 (Taiwan Forest Bureau, 1995). This digital elevation model was validated against a ground survey of more than 4000 plots, these 20 m × 25 m plots placed every 3 km throughout Taiwan with a coordinate system (Taiwan Forest Bureau, 1995). Each plot was surveyed for slope, aspect, elevation, land use, landform, and for information on canopy and sub-canopy species: tree species, tree age class, and stand age class.

This digital elevation model formed the basis of the models described below: models of sunlight, temperature, evapotranspiration, and soil nitrogen. Information on the ecological requirements of C. formosensis was derived from the 211 ground survey plots (Taiwan Forest Bureau, 1995). These plots provided the data for the temperature, moisture, and soil nitrogen requirements of C. formosensis.

Ecological Site Quality (ESQ) Model

The ESQ model is derived from the environmental response function of Botkin (1993) by eliminating the variable: maximum basal area attainable within the stand. The resulting model is based on five habitat factors:

\[ \text{ESQ} = f(AL) \times f(TF) \times f(WiF) \times f(WeF) \times f(NF) \]

Where AL is the amount of sunlight a plot receives throughout the year, TF is the annual average temperature of the plot, WiF is the annual evapotranspiration from the plot, WeF is the plot’s soil moisture, and NF is the estimated soil nitrogen in the plot. These variables were adjusted for the ecological requirements of C. formosensis (i), based on the data from 211 ground survey plots (Taiwan Forest Bureau, 1995), to calculate the ESQ for each 40 m × 40 m area in Taiwan. The higher the ESQ, the more suitable the area was expected to be for C. formosensis. Hence, we considered ESQ ≥ 0.6, which is above the mean of the range 0–1.22, as optimal. Finally, we tested the model by overlaying the locations of known C. formosensis location distribution map based on records from the 3rd Forest Resources and Land Use Inventory of Taiwan in 1995.

Effect of Sunlight \( f(AL) \)

Although C. formosensis lives on very moist and foggy slopes from 1000–2600 m in elevation (Wang, 1968; Kuo, 1995) (Fig. 1a), it appears to be shade intolerant. Seedlings have never been found below the canopy (Wang, 1968).

Therefore, we classified C. formosensis as a shade intolerant species and used the following formula from Botkin (1993):

\[ f(AL) = 2.24 \{1 - e^{-1.13(AL - 0.01)}\} \]

where AL is the light available for the tree.

We used solar radiation as a measure of this light, making no adjustments for differences in light above, within, or below the canopy.

To model the exposure to solar radiation of every 40 m × 40 m grid in Taiwan, Feng and Wu (submitted) followed the method described by Hsieh (1997). They integrated Taiwan’s digital terrain model in slope, aspect, and elevation (TFB, 1995) with the US Naval Observatory data (http://aa.usno.navy.mil/AA) on the sunrise and sunset times and the solar angle of Taiwan (http://eservice.cwb.gov.tw/docs/v3.0/Astronomy/calender/season.htm). For the vernal and autumnal equinoxes and the summer and winter solstices, Feng and Wu (submitted) recorded the solar angle and elevation for each hour from sunrise to sunset. They estimated the yearly solar radiation by averaging the solar radiation of these four days and multiplying it by the number of days in the year. This yearly solar radiation was combined with the aspect and slope data of each 40 m × 40 m grid in Taiwan following Hsieh (1997). In Taiwan, the yearly solar radiation (mean and range) was 0.8568% (0.1606~1%).

Effect of Temperature \( f(TF) \)

Taiwan has 26 climate stations (Fig. 1c) managed by the Central Weather Bureau of Taiwan. In 2001, Kao and Feng used the monthly average temperature from each station for 30 years (1970–2000 for most stations) to interpolate with a Gaussian curve the average annual temperatures for each 40 × 40 m grid in Taiwan. Kao and Feng (2001) assumed a temperature decrease of 0.6°C for each 100 m increase in elevation. For each grid, we estimated the temperature response function \( f(TF) \) for C. formosensis using the Gaussian response curve described in (Botkin, 1993):

\[ TF = e^{-\frac{(x-DEGD-\gamma)^2}{\alpha^2}} \]
mean and variance \( \text{DEGD} \) for \( C. \text{formosensis} \) from these plots: 2677.32 and 1092.76. Growth of \( C. \text{formosensis} \) is limited to temperatures >0.5°C (Su, 1987). Effect of Evapotranspiration \( f_i(W_{iF}) \)

The Water Research Bureau of Taiwan manages 815 rainfall stations (Fig. 1c). These stations record total daily evaporation. Feng and Kao (2001) used thirty years of evaporation data (1970–2000) obtained from these stations to estimate the average annual evaporation (range: 1,000 mm–7,000 mm) in Taiwan. To interpolate the annual evaporation, the following equation was used:

\[
E = \alpha \times F_i \times (W_{iF})
\]

where \( \alpha \) is the standard deviation of the daily temperatures (Botkin, 1993) of each 40 × 40 m grid. In Taiwan, the mean annual temperature in the recent 30 years ranged from: −0.3844 to 24.742 (average 18.8239). The \( \text{DEGD} \) (the number of days in each month times the average temperature for that month) and \( \gamma \) (the average of the maximum and minimum limits in temperature for the species) (Botkin, 1993) were specific to \( C. \text{formosensis} \). They were derived from the monthly average temperatures recorded from the 211 ground survey plots (Fig. 1d) containing natural populations of \( C. \text{formosensis} \) (Taiwan Forest Bureau, 1995). The estimated
classes were lithosols, cambisols, luvisols, acrisols, ferralsols, chernozems, andosols, podzols, and histosols. These corresponded to the American soil classes of entisols, inceptisols, alfisols, ultisols, oxisols, mollisols, andisols, spodosols, and histosols, respectively. The soil depths were 0–30, 0–50, and 0–100 cm.

RESULTS

Results of the ESQ for *C. formosensis* are shown in Fig. 2. The total area suitable for *C. formosensis* growth in Taiwan is 158,136,997 ha in 2,226.1 m ± 379.5 m asl. The area based on ESQ ≥ 0.6, 517,506.88 ha of Taiwan’s mountainous area may be more suitable for growing *C. formosensis*. The known distribution of natural populations of *C. formosensis*, based on the 3rd Forest Resources Land Inventory in Taiwan (Taiwan Forest Bureau, 1995) is also shown in Fig. 2. Natural populations of *C. formosensis* cover 48,639.52 ha (Taiwan Forest Bureau, 1995). The intersection of our estimate and natural populations is 24,723.52 ha. The ESQ rank distribution of suitable area and more suitable (ESQ ≥ 0.6) area are shown in Table 1. The results of each variable, \( f_i(AL) \), \( f_i(TF) \), \( f_i(WiF) \), and \( f_i(NF) \), are shown separately in Fig. 3.

Effect of Soil Moisture \( f_i(WEF) \)

Data are lacking on the level of the water table in the mountainous areas of Taiwan. Therefore, we assumed a low water table, which made soil moisture \( WEF = 1 \) (Botkin, 1993). For *C. formosensis*, we used the maximum \( DTMIN \) value (1.250) listed in Botkin (1993).

Effect of Soil Nitrogen \( f_i(NF) \)

*C. formosensis* is tolerant to nitrogen in the soil (Kuo, 1995). Therefore, we applied parameters of the tolerant class (Botkin, 1993) to the soil nitrogen response function (Botkin, 1993):

\[
f_i(NF) = \frac{-0.6 + 1.0 \times 2.79 [1 - 10^{-0.00179(AVAILN + 219.77)}] / 2.190}{AVAILN}
\]

where \( AVAILN \) is the amount of nitrogen in the soil.

There is no direct measure of soil nitrogen content in Taiwan. Therefore, the soil nitrogen content of each 40 m × 40 m grid was estimated based on soil type and depth (Batjes, 1996). The Taiwan Forest Bureau (1995) surveyed 1791 plots (Fig. 1b) for soil class, texture, depth, and type. Feng and Cheng (2003) used average and Kriging spatial interpolation to estimate the soil classes and depths for each grid square in Taiwan. For the elevations within the range of *C. formosensis* (1,000–2,600 m), they identified nine soil classes and three soil depths (Feng and Chen, 2003). The soil classes were lithosols, cambisols, luvisols, acrisols, ferralsols, chernozems, andosols, podzols, and histosols. These corresponded to the American soil classes of entisols, inceptisols, alfisols, ultisols, oxisols, mollisols, andisols, spodosols, and histosols, respectively. The soil depths were 0–30, 0–50, and 0–100 cm.

Fig. 2 Ecological site quality estimates of locations in Taiwan suitable for growing *Chamaecyparis formosensis* compared to the known locations of natural populations based on 3rd Taiwan Forest Inventory (1995).
Table 1 The area of ESQ rank distribution of suitable area and more suitable area (ESQ ≥ 0.6) in Taiwan

| ESQ value | Area of Taiwan red cypress (ha) | Percentage of Taiwan red cypress (%) | Area of Taiwan nature red cypress (ha) | Percentage of Taiwan nature red cypress (%) |
|-----------|---------------------------------|--------------------------------------|---------------------------------------|---------------------------------------------|
| 0.0–0.2   | 562942.56                       | 35.60                                | 436.32                                | 1.76                                        |
| 0.2–0.4   | 260739.84                       | 16.49                                | 3138.08                               | 12.69                                       |
| 0.4–0.6   | 240180.48                       | 15.19                                | 5346.40                               | 21.62                                       |
| 0.6–0.8   | 243003.36                       | 15.37                                | 6960.64                               | 28.15                                       |
| 0.8–1.0   | 212933.44                       | 13.47                                | 7089.12                               | 28.67                                       |
| 1.0–1.2   | 61569.44                        | 3.89                                 | 1752.96                               | 7.09                                        |
| 1.2–1.4   | 0.64                            | 0.00004                              |                                       |                                             |
| Sum       | 1581369.76                      | 100.00                               | 24723.52                              | 100.00                                      |

Fig. 3 Ecological factors used to estimate the distribution of *Chamaecyparis formosensis* in Taiwan: A) $f(AL)$ or sunlight, B) $f(TF)$ or temperature, C) $f(WiF)$ or evapotranspiration, and D) $f(NF)$ or soil nitrogen. Soil moisture, $f(WeF) = 1$, not shown.
DISCUSSION

For *C. formosensis*, sunlight and temperature may be more important in determining its possible distribution than evapotranspiration and soil nitrogen levels (Fig. 3). The fact that sunlight and temperature are highly correlated with elevation is not surprising. The effects of elevation probably control distributions of most tree species in Taiwan. Evapotranspiration is fairly high throughout Taiwan, suggesting it is probably not a limiting factor for trees in Taiwan. Soil nitrogen varies and may be important for other species (*Taiwania cryptomerioides* (Wu, 2002)). Weighting may need to be considered in different to improve the ESQ model.

The ESQ model of *C. formosensis* distribution includes almost all the mid-elevations of Taiwan (Fig. 2). This suggests that in its current shape, the model may be too general to be of real value in decisions of where to plant new stands of *C. formosensis*. On the other hand, the ESQ model included the known populations of *C. formosensis*. This is despite a cut-off of ESQ ≥ 0.6, or about half of the ESQ values (range: 0–1.22). Our ESQ model does not consider the effect of fog on solar radiation. In the medium to high elevations of Taiwan there is often fog or rain in the afternoon (Su, 1987). Therefore, solar radiation is most intense in the morning, but fairly low in the afternoon. This also means that solar radiation will vary according to aspect, with east facing slopes receiving intense solar radiation in the morning and west facing slopes receiving uniformly low solar radiation throughout the day. The Central Weather Bureau of Taiwan does collect, on an hourly basis, information on cloud cover. This information could be incorporated into our estimates of solar radiation.

After the 21st September 1999 earthquake, the location and elevations of the control points changed (http://gis210.sinica.edu.tw/ysnp/921quake/asc_report/2.htm). These points were the basis of the digital elevation model of Taiwan. Each factor in our model was based on the digital elevation model of Taiwan before the earthquake. Although the earthquake affects the current status of *C. formosensis* as well as the usefulness of predicted locations, it should not affect the accuracy of the current model. This is because all the data (the digital elevation model, the 211 survey plots, and the aerial photographs used to identify the locations of natural populations) were collected before the earthquake.

Global climate change in the form of global warming is expected to increase global temperatures and to decrease precipitation in the sub-tropics (Hughes, 2000; McCarty, 2001). These changes will affect the distributions of plant and animal communities (Hughes, 2000; McCarty, 2001). Feng and Kao (2001) modeled the effects of temperature increases of 1, 2, and 4°C on the Holdridge (1947) life zones found in Taiwan. Even a temperature increase as small as 1°C would cause changes in Taiwan’s temperate mountain forests and tropical forests. In such a future situation, the ESQ model can be used to locate new areas for planting *C. formosensis*. We have applied the ESQ model to other tree species such as *Taiwania crypomerioides*, and *Acacia confuse*, and obtained accurate results. Hence, the model may be useful in predicting or locating distributions resulting from global warming.

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