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

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SUMMARY

The 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. Into a geographic information system, 3rd Forest Resources and Land Use Inventory of Taiwan by integrated data from the climate data of 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 40m*40m 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 ESQ value are above 0.6. It showed that the model is good to evaluate the site quality for the tree species.

Keywords: 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 1000m-2600 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 excellent longevity beyond 2000 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. Science 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 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 is grown.

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 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 uses environmental variables.

Often, however, reforestation requires planting of trees in new locations. To guarantee survivorship of these trees and to conserve effort, it is important to evaluate the suitability of the new locations of reforestation. Furthermore, the wide fluctuations of environmental conditions over time, Botkin’s (1993) environmental variables is 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 40m*40m a digital elevation model of Taiwan was developed from aerial photographic of 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 20m*25 m plots placed every 3 km throughout Taiwan with 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 plots found to contain *C. formosensis* (Figure 1b). 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:

\[
\text{ESQ}_i = f_i(\text{AL}) x f_i(\text{TF}) x f_i(\text{WiF}) x f_i(\text{WeF}) x f_i(\text{NF})
\]

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 40m*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.
**$f_i(\text{AL})$ Sunlight**

Although *C. formosensis* lives on very moist and foggy slopes from 1000-2600 m in elevation (Wang 1968, Kuo 1995) (Figure 1a), it appears to be shade intolerant. Seedlings have never been found under the canopy (Wang 1968). Therefore, we classified *C. formosensis* as a shade intolerant species and used the following formula from Botkin (1993):

$$f(\text{AL}) = 2.24\{1 - e^{-1.13(\text{AL}-0.08)}\}$$

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 40m*40 m grid in Taiwan, Feng and Wu (in review) followed the method described by Hsieh (1997). They integrated the 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 (in review) 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 40m*40 m grid in Taiwan following Hsieh (1997). In Taiwan, the yearly solar radiation (mean and range) was 0.8568% (0.1606~1%).

**$f_i(\text{TF})$ Temperature**

Taiwan has 26 climate stations (Figure 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 40x40 m grid in Taiwan. Kao and Feng (2001) assumed a temperature decrease of 0.6ºC for each 100 m increase in elevation. For each grid, we estimated the temperature response function (TF) for *C. formosensis* using the Gaussian response curve described in (Botkin 1993):

$$\text{TF} = e^{-\left(-\frac{\text{DEGD} - \gamma}{2\alpha^2}\right)}$$

where $\alpha$ is the standard deviation of the daily temperatures (Botkin 1993) of each 40 x 40 m grid. In Taiwan, the mean annual temperature was in recent 30 years ranged from: -0.3844 to 24.742(average 18.8239). The 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. formosensis*. They were derived from the monthly average temperatures recorded from the 211 ground survey plots (Figure 1d) containing natural populations of *C. formosensis* (Taiwan Forest Bureau 1995). The estimated mean and variance DEGD for *C. formosensis* from these plots: 2677.32 and 1092.76. Growth of *C. formosensis* is limited to temperatures >0.5°C (Su 1987).

**f\_1(WiF) Evapotranspiration**

Water Research Bureau of Taiwan manages 815 rainfall stations (Figure 1c). These stations record total daily evaporation. Feng and Kao (2001) used thirty years evaporation data (1970-2000) obtained from these stations to estimate the average annual evaporation (range:1000mm-7000 mm) in Taiwan. To interpolate the annual evaporation (E) of every 40m*40m grid in Taiwan, they used both ordinary and simple Kriging methods and picked the model with the best fit (Burrough and McDonnell 1998). These models were then summed up to estimate the yearly average evaporation. Although there are some discrepancies in the distribution of rainfall stations (mainly in the south and central parts of the island)(Figure 1c), per-grid estimates of rainfall and evapotranspiration were considered accurate. This is because Feng and Kao (1999) developed their models using 622 stations and tested the models against the remaining 193 stations and got a good result. Potential evaporation (E\_0) was calculated based on the average monthly temperatures for each 40m*40 m grid (Kao & Feng, 2001) using the formulas described in Sellers (1965) for evapotranspiration rates for temperatures from 0-26.5°C and 26.5-38°C. We used these models of temperature and evaporation to estimate the drought effect, or WiF (Botkin 1993), of each 40m*40 m grid in Taiwan:

\[\text{WiF} = 1 - (\text{WILT}/\text{WLMAX})^2\]

where WLMAX = the drought tolerance value for *C. formosensis* and WILT = (E\_0-E)/E\_0 (Botkin 1993).

*C. formosensis* lives in very moist habitat (Wang 1968, Kuo 1995), and it is not drought tolerant (Kuo 1995). The highest level of drought tolerance for a species is measured as WLMAX (Botkin 1993). For *C. formosensis*, WLMAX= 0.53. This value is the maximum value for WLMAX listed by Botkin (1993).

**f\_1(WeF) Soil Moisture**

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

\( f_i(NF) \) Soil Nitrogen

\( C. \) 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):

\[
N_f = \{-0.6 + 1.0 \times 2.79 \left[ 1 - 10^{-0.00179(\text{AVAILN}+219.77)} \right] \} / 2.190
\]

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 40m*40 m grid was estimated based on soil type and depth (Batjes 1996). The Taiwan Forest Bureau (1995) surveyed 1791 plots (Figure 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 (1000-2600 m), they identified nine soil classes and three soil depths (Feng and Chen 2003). The soil classes were lithosols, cambisols, luvisols, acrisols, ferralsols, cherozems, 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 Figure 2. The total area suitable for \( C. \) formosensis growth in Taiwan is 158,136,997 ha in 2226.1m±379.5m asl.. The area based on ESQ>0.6, 517506.88 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 Figure 2. Natural populations of \( C. \) formosensis cover 48639.52 ha (Taiwan Forest Bureau 1995). The intersection of our estimate and natural populations is 24723.52 ha. The ESQ rank distribution of suitable area and more suitable (ESQ>0.6) area are showed 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 Figure 3.

DISCUSSION
For *C. formosensis*, sunlight and temperature may be more important in determining its possible distribution than evapotranspiration and soil nitrogen (Figure 3). The fact 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 cryptomenoides* (Wu 2002)). Weighting maybe 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 (Figure 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/ascc_report/2.htm). These points were the basis of 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. It would be caused the area change in Taiwan’s temperate mountain forest by
tropical forests even an increase as small as 1˚C. 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 cryptomerioides*, and *Acacia confuse*, and obtained accurate results. Hence, the model maybe useful in predicting or locating distributions resulting from global warming.

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LITERATURE CITED


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Fig. 1. The digital elevation model of Taiwan (A) and locations of the 211 ground survey plots containing *Chamaecyparis formosensis* (B), the 26 weather and 815 rainfall stations (C), and the 1791 soil sampling plots (D) in Taiwan. The digital elevation model (Taiwan Forest Bureau 1995) shows the elevation distribution of *Chamaecyparis formosensis*: 1000-2600 m (Wang 1968).
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).
Fig. 3. Ecological factors used to estimate the distribution of *Chamaecyparis formosensis* in Taiwan: A) $f_i$(AL) or sunlight, B) $f_i$(TF) or temperature, C) $f_i$(WiF) or evapotranspiration, and D) $f_i$(NF) or soil nitrogen. Soil moisture, $f_i$(WeF)=1, not shown.
Table 1. The area of ESQ rank distribution of suitable area and more suitable area (ESQ>0.6) in Taiwan.

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<th>ESQvalue</th>
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<th>PERCENTAGE OF TAIWAN RED CYPRESS(%)</th>
<th>AREA OF TAIWAN NATURE RED CYPRESS(ha)</th>
<th>PERCENTAGE OF TAIWAN NATURE RED CYPRESS(%)</th>
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