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Investigating the spatial heterogeneity of a subtropical montane cloud forest plantation with a QuickBird image

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Forest plantations, consisting of a single, even-age species, have long been recognized as homogeneous landscapes. However, the heterogeneity of the system may be amplified by bioclimate, which in turn can be modified by physical environments. This study attempted to assess the ramifications of two major factors, topography and the edge effect, on a subtropical montane cloud forest (MCF) yellow cypress (Chamaecyparis obtusa var. formosana, CHFO) plantation in Taiwan by integrating field observations, a high spatial resolution QuickBird satellite image and spatial layers of topography. Our regional analysis indicated that there was a negative relationship between slope and the size of CHFO. Surprisingly, we also observed a significant amount of natural broadleaf plant patches within the site, and large-size patches were frequently encountered at low elevation. For the edge-effect analysis, the area (0–30 m) along the road and natural edges yielded low canopy area and carbon (kgC stem$^{-1}$) for each individual CHFO plant, as well as low CHFO population (stems ha$^{-1}$) and carbon (MgC ha$^{-1}$) densities. Contrarily, large broadleaf plant patches were found along the road edges. Our findings suggest that topography and the edge effect may alter the spatial patterns of nutrients and bioclimate that vary the structure of the vegetation; the heterogeneity of forest plantation may be underestimated. This study also demonstrates the feasibility of integrating field, remote-sensing and geographical information system (GIS) techniques to quantify forest structure at the landscape scale. The derived structure parameters can be further utilized to model ecosystem carbon dynamics over a vast region.

1. Introduction

Plantation forests occupy about 3.8% (140 million ha) of the world’s forests and have increased rapidly (2.8 million ha year$^{-1}$) in recent years (FAO 2005). Most plantation forests consist of short-rotation and fast-growing trees, which contribute significantly to carbon (C) sequestration in terrestrial environments. Plantation forests are often even-age, pure and uniform stands. It is often assumed in plantation research (e.g. C stock estimation) that heterogeneity is negligible in this type of ecosystem (Lodhiyal and Lodhiyal 1997, Montagnini 2000, Specht and West 2003 and many others).

Montane cloud forests (MCFs) are commonly found in tropical and subtropical regions of the world (Foster 2001) and are frequently immersed in heavy fog and high humidity that would greatly reduce solar radiation (Hamilton et al. 1995). Plantations are commonly planted in this foggy zone and are habitat for several species of high
economic value such as *Chamaecyparis* spp. (Klemm *et al.* 2006). Previous studies have revealed that fog may represent about half of the annual precipitation in a MCF; the water cycle of the system could be affected significantly due to the swift cloudbank (the source of fog) height caused by climate change (Cavelier and Goldstein 1989). Pounds *et al.* (1999) found that global warming has raised the height of the orographic cloudbank resulting in less cloud immersion and increasing dryness. These micro-meteorological changes may influence the abundance of epiphytes and tree ferns that play critical roles in maintaining the health of a MCF (Foster 2001). The increased height of the cloudbank may also affect the rate of photosynthesis and respiration and reduce the capacity of $C$ sequestration in a MCF (Foster 2001, Chang *et al.* 2008, Mildenberger *et al.* 2009).

There is a close relationship between topography, bioclimate (precipitation, surface temperature and solar radiation) and soil nutrient and water contents, which are the determinants of plant growth (Briggs and Knapp 1995, Chen *et al.* 2007). Previous studies have shown that stem size and stand density are sensitive to topography; patterns in above-ground biomass (AGB) and below-ground biomass (BGB) and net primary production (NPP) allocation are also changed along topographical gradients (Clark and Clark 2000). Substrate characteristics, such as soil nutrients, texture and water availability, vary greatly across landscapes, and these may influence vegetation structure substantially (Hook and Burke 2000).

The edge effect is another pivotal factor for modifying landscape patterns. Two types of edges are commonly found in forest plantations: (1) man-made edges (e.g. roads), resulting from anthropogenic activities creating sharp boundaries (Reed *et al.* 1996), and (2) natural edges between two vegetation types, which form relatively moderate transitions (Murcia 1995). The magnitude of the edge effect declines with the increment of distance from the edge and may form its own microenvironment and biota (Malcolm 1994). Edges often have higher incident light, air and soil temperature, wind speed and lower relative humidity and soil moisture relative to the forest interior (Baker and Dillon 2000). Edges with higher incident light facilitate plant growth as a result of higher stem densities and basal areas in tropical and warm temperate forests (Williams-Linera 1990, Young and Mitchell 1994). However, plants may also be vulnerable to the edge effect resulting in high tree mortality due to low tolerance to edge-related perturbations such as strong winds (Aguiar and Tabarelli 2010).

Based on the aforementioned physical and biological drivers that may alter landscape patterns, we suspect that the structure of MCF plantations may not be as homogeneous as previously recognized. Plant structural characteristics, such as canopy area, can be precisely measured using a field method (Bonham 1989); however, the variation in forest structure is difficult to assess at the local scale. The issue may be resolved by utilizing high spatial resolution optical images (hyperspatial remote sensing) and object-based image segmentation tools (Wang *et al.* 2004) to delineate tree canopies over a large area at low cost. Consequently, biomass and $C$ stocks of the region may be estimated with the knowledge of an allometric equation and biomass–$C$ conversion coefficient of the site (Fuchs *et al.* 2009), respectively. Stem and $C$ densities and cover can also be computed after taking the area into account (Huang *et al.* 2009). Following this approach, regional assessment of forest structure variations across environmental gradients can be conducted by integrating the remote-sensing estimates with topographical data (e.g. a digital elevation model (DEM)). Therefore, the objective of this study is to investigate the spatial heterogeneity of a MCF plantation by
coupling field, remote-sensing and geographical information system (GIS) techniques. The specific questions we sought to answer were the following: (1) how do vegetation characteristics change across topographical gradients and (2) how do the road and natural boundary edges influence the vegetation structure of a forest plantation?

2. Methods

2.1 Site description

The 61 ha MCF plantation is located on Chilan Mountain in northern Taiwan (24° 35′ N, 121° 25′ E) (figure 1) across a wide elevation range (1400–1800 m asl). The climate is temperate and humid, and the mean annual temperature and precipitation are 13°C and 4005 mm, respectively. The occurrence of fog events caused by air masses lifting from the valley is about 300 days year⁻¹ and occupies 38% of the total time. The high frequency and long duration of fog events reduce solar radiation and add about 330 mm year⁻¹ of water deposition to the system. In addition, many nutrient inputs (e.g. ammonia) carried by fog may also have a pronounced contribution and account for 35–55% of total depictions (Klemm et al. 2006). Chamaecyparis obtusa var. formosana (CHFO, common name ‘yellow cypress’) is the predominant tree species of the site and was planted after clearcutting in the 1960s. The surroundings are natural, old-growth Chamaecyparis forests that have existed for at least 2000 years (figure 1). The major management objective of CHFO plantations on Chilan Mountain is to restore the populations of CHFO, which is a habitat for many endemic flora and fauna. Because of the variations in topography and climate regime, the study site affords

Figure 1. A panchromatic QuickBird image of the Chilan Mountain study site. The dark-coloured polygon outlines the boundary of Chamaecyparis obtusa var. formosana (CHFO) plantation forest surrounded by other vegetation types, and the bright-coloured irregular line within the site is an unpaved dirt road. The location of the study site (the star) with the background of a DEM is displayed in the lower right corner.
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unique opportunities to study the spatial heterogeneity of a subtropical MCF plantation. Broadleaf tree species were also recorded in the region such as *Dendropanax dentiger*, *Illicium anisatum*, *Machilus thunbergii* and *Lindera communis* (Chang et al. 2008).

2.2 Remotely sensed data acquisition and preprocessing

The biophysical properties of CHFO vegetation were characterized using a high spatial resolution cloud-free QuickBird image (Ozdemir 2008) (DigitalGlobe, Inc., Longmont, CO, USA) (figure 1). The sensor was launched in 2001 and collects one panchromatic (spectral range: 450–900 nm) and four multispectral images (blue, green, red and near-infrared (NIR) spectral ranges: 450–520, 520–600, 630–690 and 760–900 nm, respectively). The dynamic range of the image is 11 bits, and the spatial resolutions are 0.61–0.7 and 2.44–2.8 m for the panchromatic and multispectral images, respectively, dependent on the viewing angle. The image of this subtropical MCF was acquired at 10:12 (UTC) on 11 May 2009. A standard imagery product was obtained, with georegistration applied by the provider.

Two types of remote-sensing preprocessing procedures, image contrasting and atmospheric correction, were applied to the image. Image contrasting enhances the texture in an image, whereas an atmospheric correction procedure removes the atmosphere profile (e.g. molecular and aerosol scattering, water vapour) from remotely sensed data so the retrieved signals would truly reflect the properties of the land surface. We first used reported standard conversion coefficients to compute at-sensor spectral radiance (W m$^{-2}$ µm$^{-1}$ sr$^{-1}$) from the raw data. For the image contrasting, we stretched the data by subtracting the lowest measured spectral radiance from each panchromatic and multispectral band, and normalized the data range to 0–1 (figure 2). For the standard atmospheric correction, we used the radiative transfer software, Atmospheric Correction Now (ACORN) v. 6b (ImSpec LLC, Palmdale, CA, USA), to remove the atmosphere profile from the image and convert the at-sensor radiance to surface radiance (unitless). A tropic mode, atmosphere visibility and water vapour of 90 km and 20 mm, respectively, was set for ACORN by referring to the user manual (ACORN 2008) and using an international network of precipitable water vapour estimation (SuomiNet 2012).

2.3 Field CHFO total C estimation

An *in situ* CHFO allometric method was utilized to use the canopy area as an independent variable to estimate total C (Yeh 2004). AGB of 15 top layer trees of different sizes of canopies (mean ± standard deviation (SD) = 6.6 ± 3.5 m$^2$, range = 1.4–13.0 m$^2$) was harvested; the canopy area (A) was estimated by dividing it into eight equal-angle (45°) triangles (equation (1)), where $L_n$ is the projected length of the canopy area (A) from the main stem of CHFO:

$$ A = \sum_{n=1}^{8} L_n \times L_{n+1} \times \sin 45^\circ. \quad (1) $$

According to another study of this same area (Chu 2005), the ratio of AGB and BGB is 1.55 (AGB = 140.40 Mg ha$^{-1}$ and BGB = 76.60 Mg ha$^{-1}$) and the C content of
CHFO biomass is approximately 50%. Therefore, by integrating these parameters, we estimated the total $C$ storage of CHFO using the canopy area (equation (2)):

$$\ln (C) = 1.01 + 1.58 \ln (A), r^2 = 0.96. \quad (2)$$

2.4 Regional vegetation structure delineation

To delineate tree canopy areas, an advanced image fusion algorithm, the Gram–Schmidt spectral sharpening method (Fuchs et al. 2009), was applied to the contrasted QuickBird image to generate a 0.7 m multispectral image (figure 2). It was used as an input for a Feature Extraction module (Exelis Visual Information Solutions, Boulder, CO, USA). The Feature Extraction module provides object-based algorithms to extract information from an image based on its spatial, spectral and texture characteristics. The feature extraction workflow consists of a threshold setting and an optional object extraction procedure. The threshold setting is used to find objects from an image following the steps of segmentation, merging, refinement and attribute computation (for details, see Tan et al. 2010); CHFO canopy area can then be delineated.
and used to estimate the mean canopy area (m²) and C (kg stem⁻¹) using equation (2). Moreover, the stem density (stems ha⁻¹), woody C density (Mg ha⁻¹) and cover of the study site can be computed after taking the area into account. An optional procedure of the Feature Extraction module is to extract an object of interest by implementing supervised or rule-based classification. These methods have been commonly found in remote-sensing literature. Details of the classification algorithms are described in Jensen (2004). Rule-based classification was selected to delineate broadleaf plant attributes (patches and patch area) with less distinct crown shape in the image, and patch density can be computed using a GIS.

To validate the performance of image segmentation, we compared it with the field CHFO cover measured using a hemispherical (fisheye) photography approach (Rich 1990) in spring 2010. Hemispherical photographs were taken from seven transects and the canopy cover of each sampled area was derived by averaging four to five measures with a 5 m interval. Locations were geolocated using a sub metre resolution GPS (Trimble GeoXH 3000, Trimble Navigation Limited, Sunnyvale, CA, USA) in order to precisely match field observations with the spatially corresponding remote-sensing estimates. To maximize the contrast between gap openings and plant, we took photographs on an overcast day and utilized the HemiView 2.0 software (Delta-T 2000) to calculate the canopy cover.

2.5 Vegetation greenness estimation

Atmospherically corrected QuickBird multispectral bands were used to compute the enhanced vegetation index (EVI), which was used to estimate the greenness of the site. The EVI enhances vegetation signals that would not saturate in a highly vegetated area. It is also not sensitive to background noise from the soil and atmosphere profile that would typically contaminate satellite signals (Huete et al. 2002). The model for the EVI is

\[
EVI = \frac{G (\rho_{NIR} - \rho_{red})}{(\rho_{NIR} + C_1 \rho_{red} - C_2 \rho_{blue} + L)},
\]

where \(\rho\) is the surface reflectance (unitless) and the subscripts indicate NIR, red and blue bands. Note that \(G\) is a gain factor; \(C_1\) and \(C_2\) are atmosphere resistance correction coefficients; and \(L\) is the canopy background brightness correction factor. The coefficients adopted in equation (3) were \(G = 2.5, C_1 = 6, C_2 = 7.5\) and \(L = 1\). EVI values of CHFO and broadleaf plant vegetation were compared using analysis of variance (ANOVA).

2.6 Topography analysis

A 30 m DEM was acquired from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global DEM database (ASTER 2012) (figure 3(a)). We derived the topographic information (elevation, slope and aspect) from DEM using ArcGIS v. 9.3 (Environmental Systems Research Institute, Inc., Redlands, CA, USA) (Ormsby et al. 2008). Elevation and slope were regrouped to low (1469–1629 m) and high (1630–1789 m), flat (1–16°) and steep (17–31°), respectively, following the rule of equal range. Aspect was discarded from the analysis due to the homogeneity of the slope facings (only south to southeast-facing slopes on the site). To avoid interaction between elevation and slope, we further partitioned the topography into four groups (low/high elevation × flat/steep slope). ANOVA was used to test the
2.7 The edge-effect analysis

In this study, two types of edges were studied: the edges between the study site and the unpaved dirt road (man-made edges) and natural vegetation (natural edges) (figure 1). We used the 30 m DEM to compute path distance (distance taking terrain variation into account) away from the edges. According to more than 70 studies (see review by Baker and Dillon (2000)), the influence of edge effects is evident at distances less
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Figure 4. Thirty metre equal path distance (solid lines) (first eight intervals) away from (a) the road (the solid thick line) and (b) natural vegetation (Cryptomeria japonica, mature, mixed forests) edges (all but the interior core area) in the study area (figure 1). Dashed lines in (a) indicate intervals of 60, 100 and 412 m (in order) away from the road.

than 240 m in most cases. Hence, we set the distance for the first eight intervals away from the 4 m wide road to 30 m and increased the length gradually to 60, 100 and 412 m intervals (figure 4(a)). For the natural vegetation edges, we used a 30 m interval towards the core of the study area except for the last one at the centre of the site (figure 4(b)). The remote-sensing estimates of CHFO canopy area, $C$, stem density, $C$ density, broadleaf plant patch areas and broadleaf plant patch density within each interval were compared.

2.8 Sampling strategy

Remotely sensed data usually generate a tremendous number of samples, which would be an issue for a statistical test; the difference among groups may become negligible after taking the sample size into account. In addition, the spatial dependence of these data may prevent the use of regular statistical tests (Isaaks and Srivastava 1989). Therefore, it is necessary to sample the data in a random fashion (Brus and DeGruijter 1993). Yamane (1967) provided a simple model (equation (4)) to select a proper sample size:
\[ n = \frac{N}{(1 + Ne^2)}, \quad (4) \]

where \( n \), \( N \) and \( e \) are the sample size, the population size and the uncertainty, respectively. In this study, we set \( e = 0.05 \) for statistical tests. The model was applied to the topographic and greenness analyses with large samples.

3. Results

3.1 The structure of regenerated CHFO forest

In this study, we utilized high spatial resolution remote sensing coupled with object-based algorithms to delineate tree crowns in a regenerated CHFO forest. A total of 39 785 CHFO trees were delineated in the study site. The mean (± SD) canopy area of this study was 12.4 ± 9.6 m². The mean (± SD) \( C \) per individual was 138 ± 118 kgC with an estimated site \( C \) density of 119.3 MgC ha\(^{-1}\). The CHFO sizes ranged from 34 to 992 kgC stem\(^{-1}\) (figure 5). The majority (78%) of CHFO plants were less than 200 kgC stem\(^{-1}\), but the remaining small portion of large trees occupied about 43% of total \( C \). In general, the performance of object-based tree crown delineation was satisfactory in successfully outlining the texture of image based on the visual inspection (figure 2). There was a minor discrepancy (7.9%) in canopy cover estimates by the remote-sensing image segmentation and field hemispherical photography (mean ± SD = 83.3 ± 4.0% and 91.2 ± 1.2%, respectively).

Fractional cover of CHFO was 81%, and broadleaf plants occupied about 4.6% of the site (figure 3(b)). The mean broadleaf plant patch area was 6.4 ± 9.5 m². The patch density of broadleaf species was 72 patches ha\(^{-1}\) (total 4376 patches). The mean (± SD) EVI of broadleaf plant patches (0.56 ± 0.05) was significantly higher than that of CHFO (0.50 ± 0.05) \((p < 0.001; \ n \) for CHFO and broadleaf plants were 399 and 387, respectively) (figure 3(c)).

Figure 5. Proportions (%) of plants and covered areas of different size classes of *Chamaecyparis obtusa* var. *formosana* in the study site.
3.2 Vegetation characteristics across topographic variations

Elevation plays an important role in modifying bioclimate, which can have a significant influence on plant growth. However, this topographic effect was not pronounced \( (p \geq 0.2; n \text{ for high and low elevations were 780 and 733, respectively}) \) in this study for CHFO canopy area and \( C \) (table 1). Stem and \( C \) densities and cover were all slightly lower at high elevation. Unlike elevation, slope was a pivotal factor affecting plant growth. Canopy area was significantly higher \( (p = 0.04; n \text{ for steep and flat terrains were 766 and 747, respectively}) \) and mean \( C \) per tree was relatively higher \( (p = 0.06) \) on flat terrain; very slight differences were found between steep and flat terrains for CHFO stem and \( C \) densities and cover.

In contrast to the CHFO plantation, elevation had a crucial impact on broadleaf plant patches \( (p < 0.001; n \text{ for high and low elevations were 625 and 492, respectively}) \). Smaller patches with lower patch density were located at high elevation compared to those at low elevation (table 2). There was no significant difference in broadleaf plant patch area between steep and flat terrains \( (p \geq 0.2; n \text{ for steep and flat terrains were 604 and 513, respectively}) \), but areas with a steep slope had slightly higher

<table>
<thead>
<tr>
<th>Topography</th>
<th>Proportion (%)</th>
<th>Mean canopy ((\pm SD)) (m²)</th>
<th>Mean carbon ((\pm SD)) (kgC stem⁻¹)</th>
<th>Density ((\pm SD)) (stems ha⁻¹)</th>
<th>Carbon density ((\pm SD)) (MgC ha⁻¹)</th>
<th>Cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>78.8</td>
<td>12.9 ± 9.7</td>
<td>194 ± 280</td>
<td>689</td>
<td>132.8</td>
<td>88</td>
</tr>
<tr>
<td>Low</td>
<td>21.2</td>
<td>12.3 ± 8.6</td>
<td>176 ± 233</td>
<td>750</td>
<td>134.5</td>
<td>93</td>
</tr>
<tr>
<td>Slope</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Steep</td>
<td>60.5</td>
<td>12.1 ± 8.7*</td>
<td>198 ± 285</td>
<td>703</td>
<td>128.0</td>
<td>88</td>
</tr>
<tr>
<td>Flat</td>
<td>39.5</td>
<td>13.1 ± 9.7*</td>
<td>173 ± 230</td>
<td>701</td>
<td>137.5</td>
<td>90</td>
</tr>
</tbody>
</table>

Notes: Canopies touched by the boundaries of topographical groups (high versus low elevation, steep versus flat slope) are included in the analysis. Therefore, values of mean carbon, density, carbon density and cover would be slightly higher than the overall estimates.

*Indicates significant results \( (p \leq 0.05) \) according to ANOVA.

<table>
<thead>
<tr>
<th>Topography</th>
<th>Occupation (%)</th>
<th>Mean patch area ((\pm SD)) (m²)</th>
<th>Patch density ((\pm SD)) (patches ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>4.0</td>
<td>5.4 ± 6.5*</td>
<td>67</td>
</tr>
<tr>
<td>Low</td>
<td>8.5</td>
<td>7.6 ± 9.6*</td>
<td>106</td>
</tr>
<tr>
<td>Slope</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steep</td>
<td>5.5</td>
<td>6.7 ± 8.5</td>
<td>80</td>
</tr>
<tr>
<td>Flat</td>
<td>4.0</td>
<td>6.1 ± 7.6</td>
<td>67</td>
</tr>
</tbody>
</table>

Notes: Patches touched by the boundaries of topographical groups are included in the analysis. Therefore, the values of patch density would be slightly higher than the overall estimates.

*Indicates significant results \( (p \leq 0.05) \) according to ANOVA.
patch density. Note that no interactions between elevation and slope were found \( (p \geq 0.08) \) in the aforementioned statistical tests, which justified the analysis using only one topographic attribute.

### 3.3 The edge effects

The area next to the main road (0–30 m) yielded the lowest amount of CHFO canopy area (mean ± SD = 12.8 ± 10.5 m²), stem density (762 stems ha⁻¹), \( C \) (195 ± 385 kgC stem⁻¹) and \( C \) density (149 MgC ha⁻¹) compared with other 30 m interval areas (30–240 m) (figures 6(a) and (b)). The values of these CHFO structure attributes

![Figure 6](https://example.com/fig6.png)

**Figure 6.** The edge effect of an unpaved road on the *Chamaecyparis obtusa* var. *formosana* plantation within each interval (figure 4(a)). Bars indicate ranges of 95% confidence interval; proportions (%) of intervals to the study area are given in parentheses under the x-axis. (a) The mean CHFO canopy area and tree density; (b) the mean carbon and carbon density for each individual tree and interval, respectively; and (c) the mean patch area and patch density of broadleaf vegetation.
decreased gradually after the first eight intervals (240–912 m). Unlike CHFO vegetation, the mean (± SD) broadleaf plant patch area within the first interval (0–30 m) was high (7.7 ± 17.1 m²), and it stabilized with little fluctuation after the first interval (5.3 ± 7.8–7.1 ± 9.5 m²) between 30 and 400 m. The areas containing the highest mean (± SD) broadleaf plant patch areas were the farthest from the road (400–912 m) (7.9 ± 10.5–8.5 ± 11.0 m²) (figure 6(c)). Broadleaf plant patch density was the lowest within the first interval (62 patches ha⁻¹), no apparent trend was observed with the increment of distance away from the road and the area within the farthest interval (500–912 m) had the highest density (125 patches ha⁻¹).

For natural vegetation edge analysis, the areas close to the edges yielded low mean (± SD) CHFO canopy area (12.6 ± 10.3 m²), stem density (712 stems ha⁻¹), C (190 ± 380 kgC stem⁻¹) and C density (93 MgC ha⁻¹) (figures 7(a) and (b)). The trends of CHFO structural attributes were stable after the first seven intervals (30–210 m) and then dropped rapidly in the core (210–302 m). The mean (± SD) area and density of broadleaf plant patches were relatively constant across intervals (6.5 ± 9.5–7.5 ± 12.5 m² and 74–86 patches ha⁻¹, respectively). However, low broadleaf plant path area (mean (± SD) = 5.6 ± 6.1 m²) and high patch density (93.5 patches ha⁻¹) points were observed within the core of the study area (figure 7(c)).

4. Discussion

4.1 Vegetation characteristics of the subtropical MCF plantation

This study demonstrated the feasibility of utilizing hyperspatial remote-sensing techniques to characterize the vegetation structure of a subtropical MCF plantation at the landscape scale. The object-based approach can precisely outline the edge of a canopy from a sharpened high spatial resolution QuickBird image, which allowed us to estimate the CHFO structure efficiently. In the study site, plants smaller than 100 kgC stem⁻¹ occupied about half of the CHFO population (figure 5). The plantation activity after clearcutting in the 1960s resulted in the high proportion of young growth at the site. However, a considerable number (12.9%) of trees contained more than 300 kgC stem⁻¹ and up to almost 1000 kgC stem⁻¹, which was 21.6% of total C of the site. Trees with large canopies are particularly important in terms of C storage because of the nature of the log–log relationship between biomass (C) and canopy area (Jenkins et al. 2003). This reveals that conventional field measurements with the assumption of homogeneity in estimating forest plantation C budgets may not be valid to quantify the structure of MCF plantations and possibly other plantations, especially in mountainous terrain due to the variation in canopies amplified by physical environments.

The study area is designated for a CHFO plantation; however, we found that only 81% of the site was covered by CHFO canopies based on the large-scale remote-sensing observation. The remaining natural area was mainly occupied by broadleaf plant patches. In terms of the greenness of the vegetation, the EVI values for broadleaf plant patches were significantly higher than those for CHFO plantation (figures 3(b) and (c)). Broadleaf plant canopies can reflect 50% more energy in the NIR region than that of conifer trees due to foliar abundance (e.g. leaf area index (LAI)) (Zheng et al. 2004), which is positively related to ecosystem productivity (Huete et al. 2008). Carbon fluxes of a CHFO plantation could be underestimated if taking only the growth rate of plantation species into account. In summation, the heterogeneity of a forest plantation
may be underestimated at the landscape scale, which is difficult to assess at the local scale.

### 4.2 Topographic effects

Topographic effects on plant growth were not due to topography per se, but due to bioclimate and substrate contents, which are indirectly influenced by variations in

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**Figure 7.** The edge effect of natural edges on the *Chamaecyparis obtusa* var. *formosana* plantation within each interval (figure 4(b)). The data analysis and presentation are identical to those in figure 6.
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elevation, slope and/or aspect. In the study region, there is a positive relationship between precipitation and elevation. However, negative trends of temperature and solar radiation along the elevation gradient are commonly observed. CHFO adapts very well in this unique narrow ‘belt’ of foggy zone, and the effects of elevation on CHFO were negligible (table 1). However, fog can influence the bioclimate substantially, especially the reduction of the amount of solar radiation received by plants (Mildenberger et al. 2009), which is pivotal for plant growth (Chen et al. 2007). In the study area, larger broadleaf plant patches were more frequently encountered at lower elevations (figures 3(a) and (b); table 2), and the intensity of solar radiation could be the main driver altering the spatial arrangement of broadleaf plant patches. The topographic attribute that affected the growth of CHFO in the region was the declination of land surface (table 1). Several studies have shown that high concentrations of organic matter and soil nutrients can be found in flat terrain, which may facilitate plant growth (Hook and Burke 2000). Our findings indicated that slope played a crucial role in varying CHFO canopy area and possibly C storage producing larger CHFO plants on flatter terrain, which might be the effect of topography-induced substrate enrichment.

4.3 The edge effect

For the road edges, the interval nearest the main road (0–30 m) yielded the lowest canopy area and C (kgC stem⁻¹) for each individual CHFO plant, and lower population (stems ha⁻¹) and C (MgC ha⁻¹) densities for a given area than those CHFO attributes within other intervals (30–210 m) (figures 6(a) and (b)). Edges close to an open space received relatively higher light intensity, air and surface temperature and wind speed but lower humidity and soil moisture than these bioclimatic and biophysical attributes away from edges (Baker and Dillon 2000). Mildenberger et al. (2009) found that the rate of photosynthesis of CHFO was hardly reduced during very foggy conditions, and they concluded that CHFO was well adapted to low solar radiation. Therefore, the reduction of growth and population of CHFO along the road may be influenced by factors other than light intensity (e.g. soil nutrients and competition with broadleaf plants).

For broadleaf vegetation analysis, we found relatively large patches in the image near the road edges (figure 6(c)). Flat leaves can be less effective than cylindrical conifer needles at photon absorption, especially under the diffuse light conditions that predominate under cloud cover. This may explain the predominance of conifers in temperate forests where conditions are often cloudy (Chapin et al. 2002). High light intensity near the edges may facilitate the growth of broadleaf plants resulting in large broadleaf plant patches near the road. The main road in the study site was narrow (4 m), and the influence of the edge effect was rarely beyond 240 m (Baker and Dillon 2000). Therefore, large, high density broadleaf plant patches observed 500+ m away from the road may be influenced by other physical environments but not by edges. Note that there is a negative relationship between the distance from the road and the elevation (figures 1 and 3(a)). Therefore, the bioclimate at lower elevation may benefit the growth of broadleaf plants (table 2) and enhance their ability to compete for resources with the dominant CHFO plants.

The data patterns for CHFO size and abundance at the natural vegetation edges were very similar to those at the road edges, yielding low values for canopy area (m²) and C (kgC stem⁻¹) for individuals, and lower population (stems ha⁻¹) and C (MgC ha⁻¹) densities for the study site (figures 7(a) and (b)). High wind turbulence
and possibly other factors such as competition with other species near the natural vegetation can limit CHFO growth, resulting in low tree density and crown area near the edges (Baker and Dillon 2000). Lower CHFO tree density and crown area in the core region could be due to the slope effect; there was a higher slope (21°) in the core (210–302 m) compared to the other region (17°). On the other hand, the data pattern between the broadleaf plant patch area and the distance from the natural edges was erratic, and the interaction was difficult to decipher. Based on the aforementioned findings, we conclude that the edge effect is an important factor for modifying plantation landscape patterns.

4.4 Potentials and limitations

Forest is defined by high biological diversity and complex vegetation structure. Conducting a conventional field-based inventory to collect canopy information over a large region is labour intensive and costly. This study demonstrated the feasibility of utilizing advanced spatial analysis techniques to characterize the vegetation structure of the subtropical MCF plantation at the landscape scale. The object-based approach can precisely outline the edge of a canopy from a QuickBird image, which allowed us to estimate CHFO structure efficiently. Hyperspatial remote sensing provided a means to quickly and effectively measure the canopy area over a vast region (Wang et al. 2004), which is probably the only structural parameter that is highly correlated with C stocks and can be directly measured by optical remote sensing (Brown et al. 2005). In addition, canopy cover can be utilized to estimate the gap fraction in a forest (Asner et al. 2005), which is highly related to other important biophysical parameters such as the fraction of photosynthetically active radiation absorbed by green vegetation and LAI (Campbell and Norman 1998). These parameters are pivotal for modelling the C flux dynamics of an ecosystem (Huang et al. 2008).

In this study, we showed that remote-sensing techniques (image fusion + object-based delineation) can be used to quantify the vegetation structure of a subtropical MCF. However, we found that it may be difficult to detect small attached tree canopies and these will likely be mislabelled as one large tree. This two-dimensional remote-sensing limitation was commonly observed regardless of vegetation types (Huang et al. 2007, 2009 and this study), and the C overestimation could be substantial. For example, errors can be from 4.3 to 86.5 kgC stem \(^{-1}\) by misidentifying a group of clustered small trees (the category of the smallest tree size in figure 5) as larger canopies (other categories). This technical issue may be resolved by combining the outcomes of the study with lidar data measuring tree height, which would provide a unique three-dimensional perspective of a forest ecosystem (Asner 2009). This image fusion technique may help us further decipher the complexity of the vegetation structure.

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