Analysis of Natural Wind Disturbance Regimes Resulting from Typhoons Using Numerical Airflow Modelling and GIS: A Case Study in Sugi (*Cryptomeria japonica*) and Hinoki (*Chamaecyparis obtusa*) Plantation Forests

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Keywords: Air flow simulation, logistic regression model, mountain forest, wind disturbance

Abstract: Wind damage to coniferous plantation forests containing sugi (*Cryptomeria japonica*) and hinoki (*Chamaecyparis obtusa*) was studied in Japan. Wind conditions determined using an air flow simulation model, historical wind disturbance records and remote sensing measurements were integrated within a geographic information system (GIS). Based on the data set, the relationships between wind disturbances, wind speed and stand height were analyzed. A logistic analysis technique was applied to assess the probability of wind disturbance in stands that remained intact or were damaged as a result of the typhoon. The results indicate that higher wind speeds and greater stand heights increase the probability of wind disturbance in both sugi and hinoki plantation forests. The logistic regression model enabled us to predict the likelihood of wind disturbance at our study site. Our results confirmed that it is possible, using wind condition prediction software, to analyse wind disturbance in sugi and hinoki plantation forests.

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1. Introduction

In Japan, the most catastrophic forest disturbances are caused by severe typhoons. For example, the tree volume damaged by the Toyamaru Typhoon (1954) and the Isewan Typhoon (1959) was about 27.1 million m^3 and 4.1 million m^3, respectively (Tamate, 1967). Despite the extensive area of damaged forestland, forest managers are shifting to long rotations, which make forests more susceptible to the impact of typhoons. This applies to plantation forests, which comprise 40% of the forest area in Japan (Forestry Agency, 2005). A longer period without cutting leads to a greater probability of natural disturbance. For this reason, it is important to analyse the patterns of natural wind disturbance caused by catastrophic typhoons.

Many previous studies have investigated the relationship between stand condition and wind disturbance. The logistic regression model is one of the most widely-used statistical approaches available for analysing wind disturbances (Fridman and Valinger, 1998, Jalkanen and Mattila, 2000, Mitchell *et al.*, 2001, Valinger and Fridman, 1997, 1999). Comparing the logistic model to the use of a neural network, Hanewinkel *et al.* (2004) discussed the possibility of using the latter to identify forest stands that are susceptible to catastrophic winds. However, few studies have introduced air flow models into the statistical analysis of wind disturbance. In Europe, mechanistic models such as GALES (Gardiner and Quine, 2000) and HWIND (Peltola *et al.,* 1997) have been developed for analysing wind hazard risks. Talkkari *et al.* (2000) showed that the component parts of such models integrate wind disturbance risk assessment at different levels, from single trees to stands to entire regions. Their study suggested that air flow models such as WAsP (Mortensen *et al.*, 2004) have the ability to improve the analysis of wind disturbances and risk assessments. However, such models have only been used to analyse disturbance in relatively flat areas at the stand level; in such cases the wind conditions are not as complex as those encountered in Japan. Approximately 62% of Japan is mountainous (Kaizuka, 2001), with complex terrain and steep slopes. Thus, it is difficult to estimate wind conditions using linear air flow models such as WAsP (Yamaguchi *et al.*, 2003). Therefore, it is important to consider both complex terrain and unique topographic effects on wind conditions in any analysis of wind disturbance in Japanese mountain forests. To date, few case studies (e.g. Talkkari *et al.*, 2000) have investigated wind disturbances using air flow models involving local forests with complex wind conditions.

Engineers at the Research Institute for Applied Mechanics, Kyushu University, have developed a non-linear numerical simulator enabling 'computational prediction of airflow over complex Terrain' (RIAM-COMPACT) to determine the most effective positioning of wind power generation facilities (Uchida and Ohya, 1999, 2003a, 2003b). RIAM-COMPACT enables us to simulate wind conditions in areas with complex terrain and with relatively steep slopes; such areas are typical of Japanese mountain forests. It may be possible to understand wind disturbances better by introducing RIAM-COMPACT into analyses of the relationship between airflow characteristics and stand conditions.

The purpose of this study was to assess the risk of wind disturbance in mountain terrain covered by coniferous plantation forests by combining air flow simulations, historical records of wind disturbance and remote sensing measurements within a geographic information system (GIS). The study site was a managed sugi and hinoki plantation forest area in Miyazaki and Mie Prefecture, Japan. Wind disturbance probabilities at the landscape level, depending on stand and wind conditions during a typhoon, were estimated.

2. Methods

2.1. Study site

The study areas were sugi and hinoki plantation forests in Miyazaki and Mie Prefecture, Japan (Fig.1). The target forest area in Kushima city, Miyazaki Prefecture is 416.6 ha, and the highest point is 312 m above sea level. The forest is located in a warm-temperate zone, with an average annual temperature of 17.5 ℃ and rainfall of about 2270 mm. The planted trees at the study site are sugi (*Cryptomeria japonica*). The forest was damaged by the Typhoon that struck on August 18, 2006. The target forest area in Ise city, Mie Prefecture is 128.6 ha, and the highest point is 353 m above sea level. The forest is located in a warm-temperate zone, with an average annual temperature of 16 ℃ and rainfall of about 1999 mm. The planted trees at the study site are hinoki (*Chamaecyparis obtusa*). The forest was severely damaged by the Typhoon that struck on September 8, 2009.

2.2. Data sources

Forest inventory data for the study area was accessed. The forest inventory data included forest age and tree species within each stand. Stand boundaries were digitised as polygons in the GIS. The average tree height for each age distribution class in the yield table (Nakajima *et al.*, 2010) was determined for the study area. For the analysis of wind conditions, a digital elevation model (DEM) with 50 × 50-m mesh data was used to determine wind speed distribution. In order to analyse wind disturbance in Kushima city, local records of sub-compartments disturbed by wind were incorporated. These records are based on field surveys of the entire target forest conducted after the catastrophic typhoon. In total there were 536 samples from the undisturbed and 48 from the disturbed area. In order to analyse wind disturbance in Ise city, multitemporal airborne LiDAR data from target stands disturbed

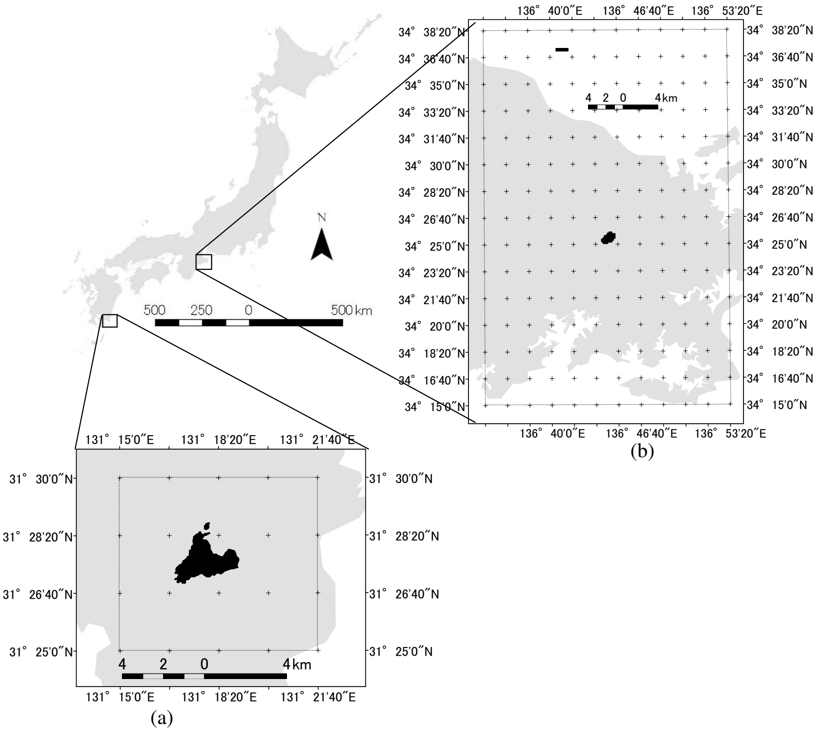

Figure 1. Location of the (a) Kushima and (b) Ise city including the study site.

Dotted line shows the wind disturbance prediction area.

by wind were incorporated. By subtracting the digital surface model (DSM) obtained in Dec. 2008, prior to wind disturbance, from that obtained in March 2010, after wind disturbance, any area of trees less than 5 m tall was identified as a wind disturbance area. In Ise city, there were, in total, 262 undisturbed and 37 disturbed areas. A stand was classified as being disturbed if it contained at least one tree that was broken or uprooted, a classification also used by Dobbertin (2002). The range of stand ages in Kushima and Ise were 4-80 and 6-98 years, respectively. The range of stand heights in Kushima and Ise were 4.8-27.4 and 3.0-33.5 m, respectively. The data sources also included meteorological information, such as maximum wind speed and wind direction observed by a local meteorological station.

2.3. Data analysis

The RIAM-COMPACT simulator was used to calculate air flow conditions. RIAM-COMPACT (Uchida and Ohya, 1999, 2003a) is a FORTRAN program based on the finite-difference approximation (FDA) method, and it uses the large-eddy simulation (LES) technique as a turbulence model. With LES, large eddy structures are calculated directly, and only eddy structures that are similar to the calculation mesh are applied. Unlike the time-averaged turbulence model known as the Reynolds-averaged Navier-Stokes equation (RANS), which was employed in a Japanese air flow model developed by Murakami *et al.* (2003), RIAM-COMPACT calculates wind conditions relatively rapidly. It can also calculate unsteady flow fields and present the results as animations. To date, RIAM-COMPACT has been used to identify optimal locations for wind turbines used for energy generation in Japan (Uchida and Ohya, 2003b). The software allows simulations of strong air flow conditions resulting from complex terrain at local levels. This software was used to analyse the relationship between wind conditions and wind disturbance. When a digital elevation model (DEM), along with the wind direction and wind speed for a site, are input into RIAM-COMPACT, it provides output wind conditions in the local area in the form of raster data. The raster data, combined with GIS data for target area, was analysed using ArcGIS9.1.

In the study area, wind disturbance caused by the typhoon was analysed by considering two factors. The first of these was wind speed; this factor plays the most fundamental role in wind disturbance. The second factor was tree height. Generally, the higher the centre of gravity of a tree, the more likely it is to be blown over. The weight of these factors may be different in sugi plantations compared to hinoki plantations, so the relationship between wind disturbance and each factor was analysed in separate models for the two tree species.

Wind conditions were estimated using RIAM-COMPACT. First, meteorological data were entered, followed by local wind disturbance records. The prevailing winds in Kushima and Ise were from the west-southwest and west-northwest, respectively; based on data from the local meteorological stations for Kushima and Ise citie indicating that the strongest winds (26.0 m m·s^{-1}, 29.4 m m·s^{-1}) are from this direction. Therefore maximum speeds of 26.0 m m·s^{-1} (Kushima city) and 29.4 m m·s^{-1} (Ise city) and west-southwest (Kushima city) or west-northwest (Ise city) winds were used in the model.

Next, maximum wind speed by stand area was determined by overlaying a raster map of the wind speed distribution predicted by RIAM-COMPACT onto a vector map of stand boundaries. For each stand, the maximum wind speed was determined and the relationship between maximum wind speed and wind disturbance was analysed. We calculated the maximum wind speed for all stands, because we considered that wind initiates disturbance at the location where the wind speed is highest. In this study, "maximum wind speed" was defined as the strongest wind predicted by RIAM-COMPACT in each stand. In this procedure, stand height in Miyazaki was estimated using a tree height growth curve. Stand height growth was calculated using Mitscherlich equation (Mitscherlich, 1909, Wang and Klinka, 1997) fitted to stand height growth according to the yield table mentioned above. In the study sites, forest administration and forestry association do not consider differences in site class because site quality does not vary much across the area. Thus, the stand height growth curve (middle site index class) derived from the yield table could be applied to the whole of the study site. We then assumed that tree height growth of all stands follows the average height growth curve in the yield table (Miyazaki Prefecture Government, 2008). The height of each stand was thus calculated. Equations [1] show the height growth curves for sugi plantation forests.

$$[1] \qquad H = 41.920 - 5.604S\left(1 - 1.027\exp\left(-0.028t\right)\right)$$

where H is stand height (m), S is site index class (1-3) and t is stand age (years)

Mitscherlich equation fitted the stand height growth well (i.e. the error rate between the estimated values and the observed values had a range of <10%). Hinoki stand height in Mie was estimated using a tree height growth curve for the Kishu area (Nakajima *et al.*, 2010).

Even compartments where only a single tree was damaged were considered to be disturbed. A logistic analysis (Collett, 1991) technique was used to assess the probability of wind disturbance for the disturbed stands (indicator for wind disturbance: $iwd = 1$) and the undisturbed stands ($iwd = 0$). When using the logistic analysis, the probability (p) of a stand being disturbed was modelled as a function of stand and wind conditions (x). Factors included in the function were maximum wind speed and average stand height, as mentioned above. Using these factors, the probability of disturbance (p) was calculated by:

$$[2] \qquad p = \frac{\exp\left(a_0 + a_1x_1 + a_2x_2\right)}{1 + \exp\left(a_0 + a_1x_1 + a_2x_2\right)} \times 100$$

where x_1 is maximum wind speed (m·s^{-1}), x_2 is average stand height (m) and a_0, a_1, a_2 are constants

The wind disturbance probability was predicted on the basis of the logistic analysis. The software package Excel statistics 2006 (Social Survey Research Information Co., Ltd., 2006) was used for the statistical analysis.

3. Results and Discussion

By comparing contour lines and wind speed, it can be seen that the wind speed was generally strongest at higher elevations (Fig.2).

The logistic analysis produced the following probability assessment models for sugi [3] and hinoki forests [4], respectively:

[3] $$p = \frac{\exp(-4.994 + 0.116H + 0.024Ws)}{1 + \exp(-4.994 + 0.116H + 0.02Ws)} \times 100$$

[4] $$p = \frac{\exp(-11.173 + 0.131H + 0.247Ws)}{1 + \exp(-11.173 + 0.131H + 0.247Ws)} \times 100$$

where p is the percentage of wind disturbance (%), H is average stand height (m) and Ws is the maximum wind speed ($\mathrm{m{\cdot}s^{-1}}$).

The fit of the model was significant. P values for stand height in sugi plantation forests were less than 0.01. In hinoki forests, the p values for stand height and wind speed were less than 0.01. The constants representing wind speed were positive in both sugi and hinoki forests. This means that the higher the wind speed, the higher the percentage of disturbance. However, unlike stand height, the variable 'wind speed' was not highly significant ($p > 0.001$).

Based on the logistic analysis, predictions were made for disturbance in sugi and hinoki forests (Fig.3). The probability of wind disturbance increases with stand height. Based on this relationship, the percentage wind disturbance resulting from an increase in average tree height in a stand can be predicted. The predicted wind disturbance probability of hinoki stands composed of trees shorter than 25 m under wind speed

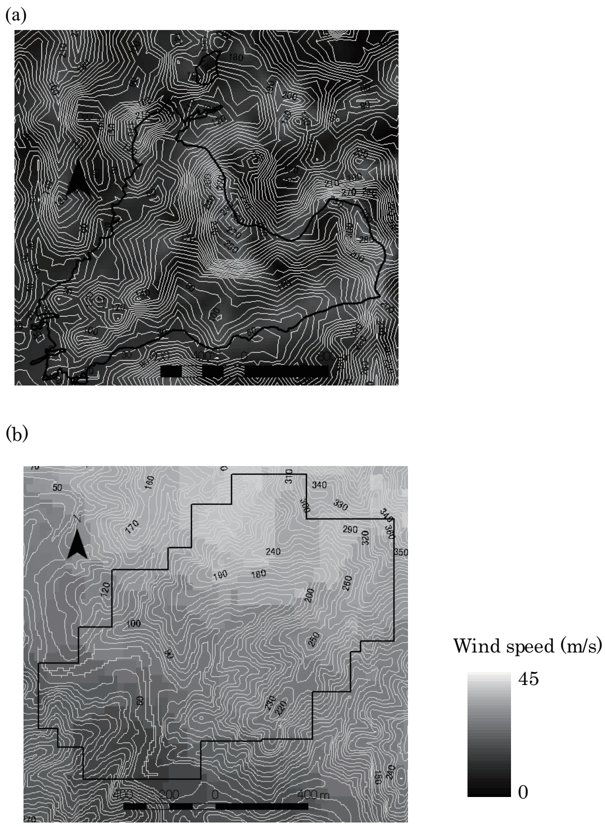

Figure 2. Wind speed distribution predicted by RIAM-COMPACT in (a) Kushima and (b) Ise city.
The black lines indicate the target forest area.

25 m/s never exceeds that of sugi stands. Because there were the differences in the geography and wind conditions at the two study sites, it was difficult to compare directly the wind disturbance probability under the sugi and hinoki trees. In order to analyse the difference in wind disturbance probability between the sugi and hinoki stands, it

would be better to compare the wind disturbance probabilities for sugi and hinoki at a single study site. Therefore, the next challenge is to conduct the same analysis in a forest area containing both sugi and hinoki that has been affected by wind disturbance.

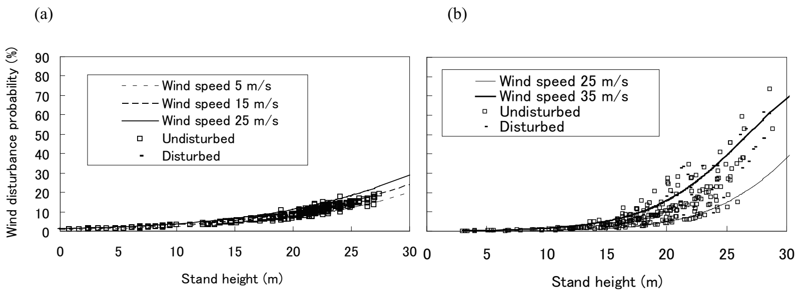

Figure 3. Predicted probability of wind disturbance and stand height

For logistic equations 3 and 4 (dashes), and for the logistic function with fixed wind speed values ($m{\cdot}s^{-1}$) of 5 (thin dotted line), 15 (bold dotted line), 25 (solid line) and 35 (bold line), in (a) sugi plantation forests and (b) hinoki plantation forests.

Our results for sugi and hinoki showed that taller stands are more likely to experience wind disturbance. Mayer *et al.* (2005) also showed that stand height was significantly related to wind disturbance. It follows that if a tree is taller, it is more likely to fall over because it is less stable (Lohmander and Helles, 1987, Ni Dhubhain *et al*, 2001, Quine, 1995).

As described above, differences in wind disturbance probabilities for coniferous sugi and hinoki forests in a complex mountain area were estimated and modelled (Fig.3). The percentage of wind disturbance was also successfully quantified. Previous studies using a logistic regression model have analysed the relationships between wind disturbance and many factors that influence wind conditions, such as declination, slope aspect and elevation. For example, Jalkanen and Mattila (2000) analysed the relationship between percentage wind damage and elevation and showed that there was no strong relationship between the two. Mitchell *et al.* (2001) used ground slope, aspect and elevation as topographic variables related to wind disturbance and selected ground slope and elevation for use in their logistic regression models. As mentioned above, such previous studies analysed the relationships between wind disturbance and individual variables in terms of wind speed. However, strong winds are directly related to disturbance. Based on an analysis of the relationships between wind disturbance and topographic conditions, Dobbertin (2002) suggested the need to incorporate modelled wind speed in wind risk models in order to improve the accuracy of such models for predicting storm damage to forests. In addition, it is difficult to study changes in wind condition in combination with complex factors in mountain forests, which have relatively complex terrain and steep slopes. Using a wind prediction system such as RIAM-COMPACT, however, the relationship between wind disturbance and wind speed can be analysed directly. Talkkari *et al.* (2000) also investigated the relationship between wind speed and wind disturbance in northeastern Finland. In their study, the elevation ranged from 135 to 385 m, and wind speeds were less than 20 $m \cdot s^{-1}$. In our study, the elevation ranged from approximately 50 to 300 m, and the wind speed ranged from 5 to 25 $m \cdot s^{-1}$ (Kushima city) and 25 to 35 $m \cdot s^{-1}$ (Ise city). Our data suggest that it is possible to analyse wind disturbances using wind condition prediction software that can simulate the strong airflow conditions created by the complex terrain in Japanese forests.

4. Conclusions

We analysed wind disturbance by combining an airflow simulation and wind disturbance records, using GIS data for a mountain forest. The study site was a forest area managed by the forest association and forestry department of Jingu Shrine in Kushima and Ise cities. Based on abundant information about wind disturbance, wind disturbance at the local level was estimated. The combination of GIS and a wind condition prediction system enabled us to analyse wind disturbance in relation to stand and wind conditions. We found that higher wind speeds and stand heights increase the percentage of disturbance.

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数値風況モデルと地理情報システムをもちいた台風による風倒被害の分析：スギ・ヒノキ人工林を事例として

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要約: 本研究は、スギ・ヒノキからなる針葉樹人工林の風倒被害を対象とし、風況シミュレーション、風倒被害履歴およびリモートセンシングデータを GIS(地理情報システム) 上で統合した。これらのデータセットを基礎に、風倒による自然撹乱と風速および林分樹高の関係を解析し、台風による被害林分および無被害林分における風倒被害の発生確率を評価するためにロジスティック分析を適用した。その結果、スギ・ヒノキ人工林のいずれにおいても風速および樹高が高いほど、風被害確率が増加することが示唆された。さらに、ロジスティック回帰モデルによって、対象地において風倒被害の傾向を予測するとともに、風況予測ソフトウェアをもちいて、スギ・ヒノキ人工林における風倒被害を解析し得ることを確認した。

キーワード: 風況シミュレーション, ロジスティック回帰モデル, 山林, 風害