論文の内容の要旨

森林科学専攻
平成１６年度博士課程　入学
氏名：上村佳奈
指導教員名：白石則彦

論文題目　**Developing a decision-support system for wind risk modelling as a part of forest management in Japan**
（日本における森林経営の風害リスク軽減を目的とした
意思決定支援システムの開発）

1. Introduction

For a long time, forests in Japan have faced several risks. In particular, abiotic risks such as wind, snow, and fire have the potential to trigger enormous damage. Wind damage has become a critical issue in Japan, because the damage has been often found in semi-mature or mature forests. However, risk assessment and management of wind risk has not yet been well developed in Japan. This is partly because there are regional differences in the risk frequency and because only a few studies have until recently focused on the issue. This dissertation aimed to develop a decision-support system for risk assessment with a special focus on wind damage. In particular, typhoon damage was targeted. The system consisted of a mechanistic wind damage risk assessment model, an airflow model, a growth model, decision trees analysis, geographic information system (GIS), and labour efficiency analysis. In particular, a British empirical-mechanistic model (GALES) was seen as a key model for the decision-support system. Thus, this dissertation was composed of the following six chapters: Introduction; Literature review; Acquisition of tree parameter for wind risk model; Adaptation and validation of wind risk model; Construction of a decision-support system; and Discussion and Conclusions.

2. Literature review

Current methods of wind risk assessment are classified into three approaches: observational/empirical, statistical, and mechanistic. The former two methods are effective only when sufficient damage data are available; they can only be utilized for regions where wind damage is frequently observed and the damage data is adequately recorded. In addition, these methods are rarely used for estimating future damage due to the lack of mechanistic information on trees and stands. The mechanistic method is based on the mechanistic behaviour of trees and stands (a mechanistic wind risk assessment model) and wind climate (an airflow model). Thus, it is useful to simulate future risk as a function of thinning strategies. In particular, one of the mechanistic models, GALES, has been widely adapted for use in a number of different environments in order to simulate the critical wind speed causing wind damage at the centre of stand.

3. Acquisition of tree parameters for wind risk model

To obtain the parameters for GALES, this chapter focused on tree-pulling experiment in which trees were artificially pulled down by using a wire cable. The tree-pulling experiment was carried out for sugi (*Cryptomeria japonica* (L.f.) D.Don) and hinoki (*Chamaecyparis obtuse* (Sieb. Et Zucc.) Endl.) in the experimental forest of the University of Tokyo in Chichibu, Saitama Prefecture, Japan. Ten sugi trees and nine hinoki trees were successfully pulled over. Six sugi trees and eight hinoki trees were overturned, and four sugi trees and one hinoki tree were broken. By calculating the maximum bending moment at the stem base ($TM_{max,total}$), the relationship between $TM_{max,total}$ and stem weight (SW) was determined, so that the results could be used for the GALES parameters. To calculate the critical wind speed leading to overturning, the linear relationships were $TM_{max,total} = 229 \times SW$ ($R^2=0.94$; sugi) and $TM_{max,total} = 244.2 \times SW$ ($R^2=0.96$; hinoki). The average values of modulus of rupture (MOR) for stem breakage were calculated as 42.5 MPa (sugi) and 71.6 MPa (hinoki).

4. Adaptation and validation of wind risk model

As a mechanistic approach to wind risk assessment in Japan, a modified version of the GALES model, namely ForestTYPHOON, was developed with an airflow model, WAsP8, in order to estimate the wind damage in sugi and Japanese larch (*Larix kaempferi* (Lamb.) Carriére) stands in Himi (Toyama prefecture) and Mt. Yotei (Hokkaido prefecture) regions. Because these models were originally constructed for European conditions, it was necessary to adjust the models for the Japanese environment and wind damage phenomena caused by typhoons. Before wind damage estimation, the model parameters were statistically tested to show whether they were appropriate for our study areas. Although limited information on tree-pulling experiments was available in Japan, significant agreement was obtained between the relationships for both species in different locations.

Wind damage estimation was conducted by using ForestTYPHOON with field survey data, forest inventory data, and WAsP with wind climate data observed at AMeDAS (meteorological) stations. The estimated damage was compared to the actual typhoon damage in 2004. The initial damage estimates did not show good agreement with the actual damage. The desired accuracy level was set to 70% based on the validation of GALES in Britain. For sugi, the accuracy calibrated with the estimated local wind speed (EWS)+30% and the critical wind speed (CWS)±1 m/s was at this level. The Yotei region showed suitable accuracy with *EWS*+30% and *CWS*±1.5 m/s, although the accuracy level was not satisfied in the northern area, because severe terrain effects were caused by Mt. Yotei and because there were insufficient wind climate data. This study suggests that the methods to estimate wind damage might be limited to particular terrain conditions; thus, further study is necessary to determine the sensitivity of the CWS calculated from ForestTYPHOON and alternative methods of wind climate estimation under different conditions.

5. Construction of a decision-support system

This chapter focused on the construction of a decision-support system with different components: labour efficiency to choose a suitable thinning method, spatial and temporal analysis to prioritise the target area using GIS, and decision trees to choose a course of silvicultural actions. In the system, the probability of wind risk was determined by using a binary rule of risk for four wind directions. Consequently, the decision trees indicated the significant stand characteristics relating to wind damage. Therefore, this system could suggest appropriate management actions to deal with the uncertainty of typhoon wind damage. The system consisted of the following five steps (Figure 1):

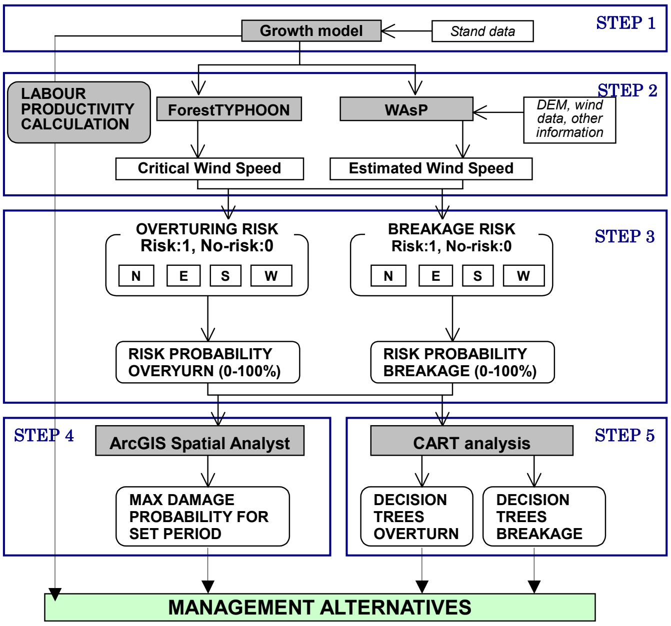

Figure 1. Framework of the decision-support system

<u>STEP 1 Stand growth simulation and labour productivity for thinning</u>: Stands conditions were simulated for a certain period of time using a growth model according to management scenarios (thinning and harvesting).

<u>STEP 2 Estimating critical wind speed, local wind speed, and labour productivity</u>: The mechanistic method (consisting of ForestTYPHOON and WAsP) was applied to estimate wind risk by comparing the CWS and the EWS. The outputs were the CWS values of two failure types (overturning and breakage) and the EWS values for four directions (north, south, east, and west).

<u>STEP 3 Calculating the probability of windthrow damage</u>: First, the existence of wind risk was defined by a binary rule, i.e. expected wind damage in a stand was 1, and no wind risk was 0. Second, two methods were applied to define the probability of wind damage risk for spatial and temporal analysis and for the decision trees. For the spatial and temporal analysis (by GIS), all values of probability were averaged and then multiplied by 100 to obtain a percentage: 0% indicates no probability, and 100% indicates the highest probability of wind damage. The highest risk suggested that the stand had a high possibility of wind damage of both failure types caused by wind from any direction. For the decision trees analysis, the probability of wind risk was calculated in terms of two failure types by averaging the binary values, which resulted in two kinds of risk values (overturning and breakage).

STEP 4 Spatial and temporal analysis: GIS raster layers were created based on the averaged probability calculated in Step 3. The number of layers was dependent on the procedure of the growth model.

STEP 5 Decision trees analysis: Classification and Regression Trees (CART: Decision Trees) were created in terms of overturning and breakage. The wind risk probabilities defined in Step 2 were used as dependent variables; independent variables were selected from geographical and tree characteristics. There were two types of independent variables: constant and temporal. The constant independent variables were based on geographic characteristics, which scarcely changed. The temporal independent variables were found in the aboveground characteristics, which change depending on tree growth.

At the end of the system, management alternatives could be made by prioritising (GIS outputs) and choosing courses of action (labour productivity and decision trees). The decision-support system for typhoon wind risk is helpful for decision makers who have certain limitations of forestry activities, such as available labour and accessibility.

6. Discussion and conclusion

The decision-support system was discussed from the perspective of forest management (Figure 2). In particular, it was important to classify management alternatives to sharing, accepting, and reducing risk so as to decide actions. For instance, the alternatives could suggest management strategies such as having forest insurance, recreating forest composition (e.g. roads and preserved stands), and prioritising locations to receive thinning and harvesting. However, several requirements were found to further develop forest management strategies for wind damage risk. For the decision-support system, it was necessary to improve the airflow model for complex terrain, to incorporate gap and stand-composition analysis, and to expand the model to other tree species. Risk management also required analysing post-damage phenomena, such as the economical impact on timber markets. These system and management should be also simplified for use in actual forest management. In addition, the scale of forest management should be clarified to allow flexible actions for a period of time. More importantly, the procedures needed to include other abiotic risks by using various modelling techniques of abiotic damage. Such an integrated management strategy would become a strong tool to provide suitable alternatives to balance the conflicts arising from managing different risks, and thus allow stable forest management in the long term.

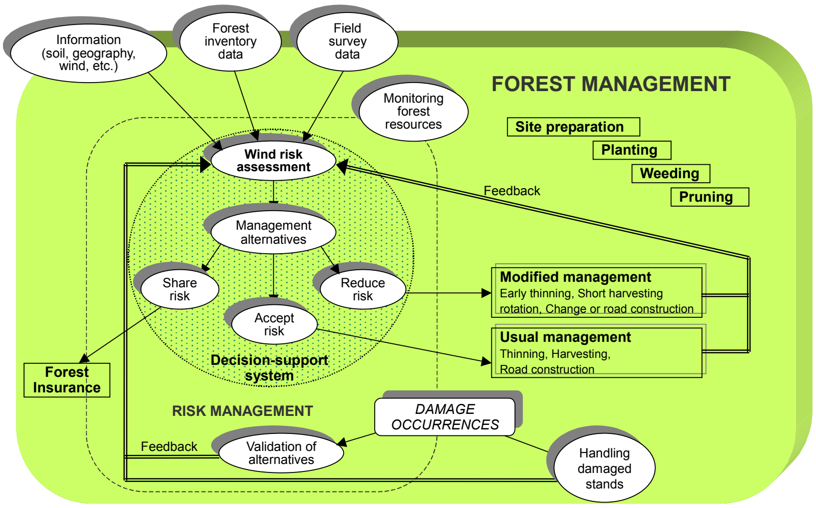

Figure 2. Framework of forest management