論 文 の 内 容 の 要 旨

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論文題目　A research on developing optimal management plans with productivity and risk considerations for multi-species industrial tree plantations in the Philippines
(フィリピンにおける多樹種産業造林の生産性とリスクを考慮した最適計画の策定に関する研究)

In the Philippines, the significant loss of primary forest cover impelled industrial tree plantations to a major role in satisfying annual wood production requirements. Recently, wood production from plantations contributed more than 90% to the total annual log production of the country. However, the sustainability and stability of wood production from plantations are being jeopardized by the emergence of issues and limitations from the way they are developed and managed. In particular, management plans fail to implement proper species-site matching, lack provisions to include risk considerations, and fail to schedule timber harvests in an optimum manner. These limitations result from general problems such as lack of knowledge and limited availability of practical approaches for determining site productivity, risk assessment and harvest-schedule optimization. These issues and limitations are the motivations of this research study.

The study intended to seek approaches and solutions to the identified problems and consequently improve the current state of plantation development and management practices in the country. In order to do this, three sub-studies with interrelated objectives were conducted. The general objectives of this study are to, 1) determine site productivity for different target plantation species using the ecological characteristics of the site, 2) assess the site's probability of risk to wind damage brought by storms and typhoons, and 3) develop species-site assignment models that consider site productivity and risks and concurrently optimizes management objectives and timber harvest

schedules.

The objectives of the study were applied on a case-study area in Caraga region, Mindanao, Philippines. The study site is a medium-scale industrial tree plantation area of softwood species located in a region where is there is a high prevalence of similar kind of plantations. In particular, the study focused on the 3,500-ha plantation area of the site in which four major plantation species are currently grown. These species are *Paraserianthes falcataria, Endospermum peltatum, Acacia mangium,* and *Gmelina arborea* which are grown to produce raw materials for the manufacture of veneer, pulpwood, matchwood and others. These particular species are also the target species indicated in the study.

Plantation managers recognize the importance of proper species-site matching to achieve maximum growth of tree species. However, the lack of knowledge of the site's productivity impedes its implementation. In order to address this issue, the study sought the approach of determining site productivity from prevailing ecological characteristics. For each target species, the site productivity in terms of site index (SI) was estimated. Inventory data from various years and ecological factors mostly derived from digital elevation model (DEM) were used. Using multiple regression analysis, SI predictor models were developed and major ecological factors limiting site productivity for each species were identified. Results show that the accountability of best-fit SI predictor models ranges from 36% to 61%. Moreover, depending on the species, the predictor models included factors such as elevation, wetness index, exposure to direct solar radiation, length of sunlight duration and amount of annual rainfall. Common variable models using the elevation variable were also developed for all species to facilitate prioritization of multi-species over limited areas. The common variable models have lower accountabilities than best-fit models that range from 16% to 49%. Across target species, the best-fit models included different combinations of ecological variables confirming that site productivity is species-specific and is controlled not only by a single ecological factor, but by their combinations. Translating the results of SI models into maps showed the distribution of site index variation for each species across the study area. It also provided estimates of site productivity on areas inside the study site where the target species are not currently grown. These results demonstrated the

feasibility of practical determination of site productivity from ecological factors. Further, this is an important information for plantation managers particularly those who manage multi-species plantations.

Risks to plantations come in many forms such as pest attacks and diseases, fire, wind damage and others. Considering these risks depending on their prevalence should be an important component of plantation management plans. The problem, however, is that risks that were not conceived before may have become relevant in the present. Such is the case of the study area where the unprecedented increase in the frequency of storms and typhoons is now causing serious wind damages to plantations. In this consideration, the site's probability of risk to wind damage was estimated empirically using logistic regression analysis. Specifically, the influence of stand-level attributes such as average stand height (ASH), elevation (Elev) and topographic exposure (TOPEX) on damage probability were assessed. For the analysis, post-storm inventory data from 2012 Typhoon Bopha in combination with previous stand inventory data were used. Logistic regression analysis yielded the best-fit model with the form,

$$P = \frac{\exp(-31.065 + 0.292\text{ASH} + 0.038\text{Elev} + 0.228\text{TOPEX})}{[1 + \exp(-31.065 + 0.292\text{ASH} + 0.038\text{Elev} + 0.228\text{TOPEX})]}$$

where, P is the probability of wind damage. Results showed that all three stand-level variables are influential and that damage probability has a direct relationship with the variables. By considering constant terrain conditions, the effect of average stand height was determined. Results indicated that there are critical average stand height levels which put each site at high risk of being damaged. Critical stand heights of 25 m, 20 m and 10-15 m were identified for low, medium and high-risk level sites. This information, when combined with site productivity, could be used as a basis for determining risk-sensitive rotation ages at which certain species can be grown while reducing wind damage to plantation. Moreover, variables used were derived from DEM thereby addressing the high-cost issue associated with developing damage probability models. Amidst the issue of climate change and the projected increase in weather disturbances, these results can improve management plans and make them relevant and responsive to

changing times.

Finally, site productivity and risk considerations were integrated into an optimization model to develop species-site assignment models that maximize management objectives and ensure stability of future harvests. Results revealed feasible solutions to set management objectives using integer programming with binary variables. The study site was divided into management units called compartments and the optimum species assignment for each unit was identified using site productivity and risk-sensitive rotation ages. Results indicated that species-site assignment varies with different management objectives. Fast-growing and high-volume yielding species are prioritized in maximizing harvested volume objective. On the other hand, fast-growing and shorter rotation species are given more priority in the objective of maximizing net present value (NPV). In both objectives, *E. peltatum* was given the highest priority among target species. The risk-sensitive rotation ages used in optimal models revealed that in considering risks of wind damage, generally shorter rotation ages than usually practiced should be implemented. However, despite shorter rotation regimes, the optimal timber harvest schedules still yield high volumes of harvest and positive NPV for the 50-year planning period. Further, the resulting optimal models produced a harvest schedule with minimal fluctuations in harvested volume per working period, hence stable flow of income. Moreover, in pursuing both objectives, an adequate growing stock is ensured at the end of the planning period. Comparing optimal species-site assignment models and current species composition revealed that about 59% of the compartments are not planted with the recommended species. This indicates that the potential of the site in terms of timber volume production and NPV is not being maximized. These results demonstrated a scientific yet practical approach to solving plantation management problems related to site productivity, risks, species-site assignment and harvests. The integration of these results and approaches will improve plantation management and planning making them more flexible, scientifically-derived, relevant and responsive.