Working Papers of the Finnish Forest Research Institute 50: 74–87

Structure and Management of Complex Stands – Key Features and Study Methodology

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In even-aged single species plantation forests, it is sometimes sufficient to analyze and predict growth and yield in terms of simple stand attributes. Generally, diameter distributions and stem volume prediction is usually involved for deal with dimensions and timber products. In the management of indigenous multiple-species forests with complex structures and dynamics, the information needs are more intricate. Tree and species interaction, multiple layers and clustered spatial distributions, treatments, regeneration and other factors tend to constitute a system of mutual interactions which must be attended to in management for specific objectives. Some of the basic features, in all probability relevant for studies in miombo woodlands too, are introduced and demonstrated in terms of two studies in mixed uneven-aged stands. Outlines for potential applications in project activities are discussed.

1 Introduction

Given the vast extent of the ecosystems and their importance in rural livelihood and local economies (Campbell 1996), and articles by Hamza and Kimwer, Makonda and Gillah, Monela and Abdallah in this publication), remarkably little research efforts have been focused on the structure, dynamics, and management of the miombo woodlands of Africa. Uncontrolled, often illegal use, and over-exploitation of the resources has resulted in rapid deterioration in many areas. Economic, social, and ecological sustainability of the ecosystems is endangered. Current experience in Tanzania and elsewhere indicates that participatory management strategies have the potential of providing means to decelerate and even reverse the adverse developments (articles by Hamza and Kimwer, Lulandala and Chitiki, Makonda and Gillah, Nyberg, in this publication). The challenges are huge of course. The complex array of uses, products, benefits, goals, and stakeholders makes each management situation and its information needs unique.

One of the key questions is which species, types, and sizes of trees to promote, and how to do it in order to establish and sustain a balance of outputs and goals (Makonda and Gillah, Nshubemuki and Mbwambo, in this publication). Furthermore, the silvicultural information base for the development of feasible management regimes is often underdeveloped for Tanzanian (Nshubemuki and Mbwambo, in this publication) and other miombo areas (e.g. Chidumayo and Frost 1996, Musokonyi 1998).

Many extension efforts still tend to focus on disseminating technical tree-planting packages, while the true potential of miombo woodlands could probably be harnessed and developed in a much more cost-effective way through the utilization and management of the existing indigenous stands. Similarly, the approaches used to develop the management regimes for the plantation forests with their uniform structures, dynamics, and management regimes (e.g. Pukkala 1998, Valkonen et al. 2000) certainly would not work for the complex miombo stands. In miombo woodlands, analysis methods capable of accounting for the inherent and human-induced variability within the stands are needed. They must be able to deal with the variation in characteristics, role, and mutual interaction of individual trees and regeneration. Ecology, site, management, and disturbances all have their influence of both tree and stand level attributes. Primary examples of successfulness of such applications are presented by Nshubebuki and Mbwambo, and Isango (in this publication).

The purpose of this paper is to introduce some approaches and methodologies of silvicultural and forest growth and yield research that could constitute effective tools for research and management in the structurally complex miombo stands. They generally consist of intensive measurements on permanent, semi-permanent, or temporary sample plots, including elaborate measurements on structurally and functionally important tree dimensions, tree growth, and regeneration. The measurements and analyses are often spatially explicit, i.e. the complex interactions of the various kinds and sizes of trees can be accounted for in terms of the stand structure and its manipulation at the individual tree level.

The analyses are more or less related to modeling. Simulation for interpolation and prediction are often applied. The results can be communicated through computer illustration of the results of the analyses in terms of alternative treatments within the limitations of the data. One case study (Piirto and Valkonen 2005) with indigenous uneven-aged stands of Monterey pine (*Pinus radiata* D. Don) are used to demonstrate the methodologies and applications in this paper. The study was based on sample plots measured just once. Tree increment data was acquired through coring, and the regeneration survey represented just one point in time. Therefore, results from another regeneration data set from Finland (Ollikainen 2001), based on repeated measurements during a longer period, are also introduced.

2 Analysis Framework

The purpose of the research on complex stands usually is to provide tools for analyzing the stand dynamics both in great detail and as a system of mutual interdependencies:

1. What kind of stand structures and species compositions do the stands currently display?
2. How are trees of different species and sizes surviving, growing, and developing in stem form and wood products in the stands?
3. How much regeneration of different species is currently present ?
4. How much regeneration is established annually, how much of it survives, and how do the surviving individuals develop?
5. What kind of treatments would best promote the development of desirable trees (species, sizes, forms, products)?
6. What kind of management would be best in promoting the desired balance of wood and non-wood products, benefits and values on a sustainable basis?

It is comprehensible that such elements constitute a system where none of the elements is independent of the others. The basic elements at the top of the list can be, and usually are, initially analyzed one by one, providing the basic insight to the key constituent parts. However, as the issues become more complex and comprehensive down the list, the role of more general and flexible in terms of models tends become greater.

3 Stand Structure

Stand structure has three main components: species composition, tree size distribution, and spatial distribution. They are generally interdependent in terms of the ecological properties of trees, site, management, and other factors. The current stand structure is a product of past development. Numerical analysis tools may often provide useful information on selected features in detail. They involve different types of diversity and dispersion indices and spatial analyses, often utilizing geostatistics. A comprehensive insight in the essential attributes related to management goals is more useful for practical purposes. The number, proportion, and social and spatial status of individual trees of species, forms and sizes is the primary issue. There is also a link to considerations on what kind of growing environments would be best for the desirable trees to regenerate and develop.

Examples of tree size (diameter) and species distributions in the Monterey pine study are shown in Fig. 1. Note that Monterey pine was the central species to promote in this case. Other species were considered to have mainly adverse influences through competition for resources and growing space. Also note that only continuous-cover management is permitted in the area by regional forestry statutes.

Fig. 1A shows a typical complex, mixed structure where both Monterey pine, Douglas fir *(Pseudotsuga menziesii var. menziesii* (Mirbel) Franco), and broadleaf species consisting mainly of shade-tolerant oaks like Coast live oak (*Quercus agrifolia* Nee) and Shreve oak (*Quercus parvula var. shrevei* C. H. Muller). Lots of large and mid-size pine and Douglas fir is present, but the numerous small diameter classes are becoming dominated by the oaks. Since the primary goal with overwhelming priority is the sustainability of Monterey pine in the stand, structures like the one displayed in Fig. 1B would be much more favorable. In the lack of wildfires and management, many parts of the forest are becoming like in Fig. 1C, where Monterey pine is no longer capable of sustaining its presence due to broadleaf invasion resulting in complete canopy coverage and intense shading.

In terms of similar diameter distributions, the spatial distribution of trees of different sizes and species can be important. Fig. 2A illustrates the distribution on the plot shown in Fig. 1A. In this case the spatial distribution is randomly dispersed. In Fig. 2B, a plot with a similar diameter and species distribution, the spatial structure is strongly segregated by species.

In this way, the principal constituents of stand structure can be easily explored and demonstrated for management purposes. Index or geostatistics-based analyses were not considered worthwhile in the example study (Piirto and Valkonen 2005).

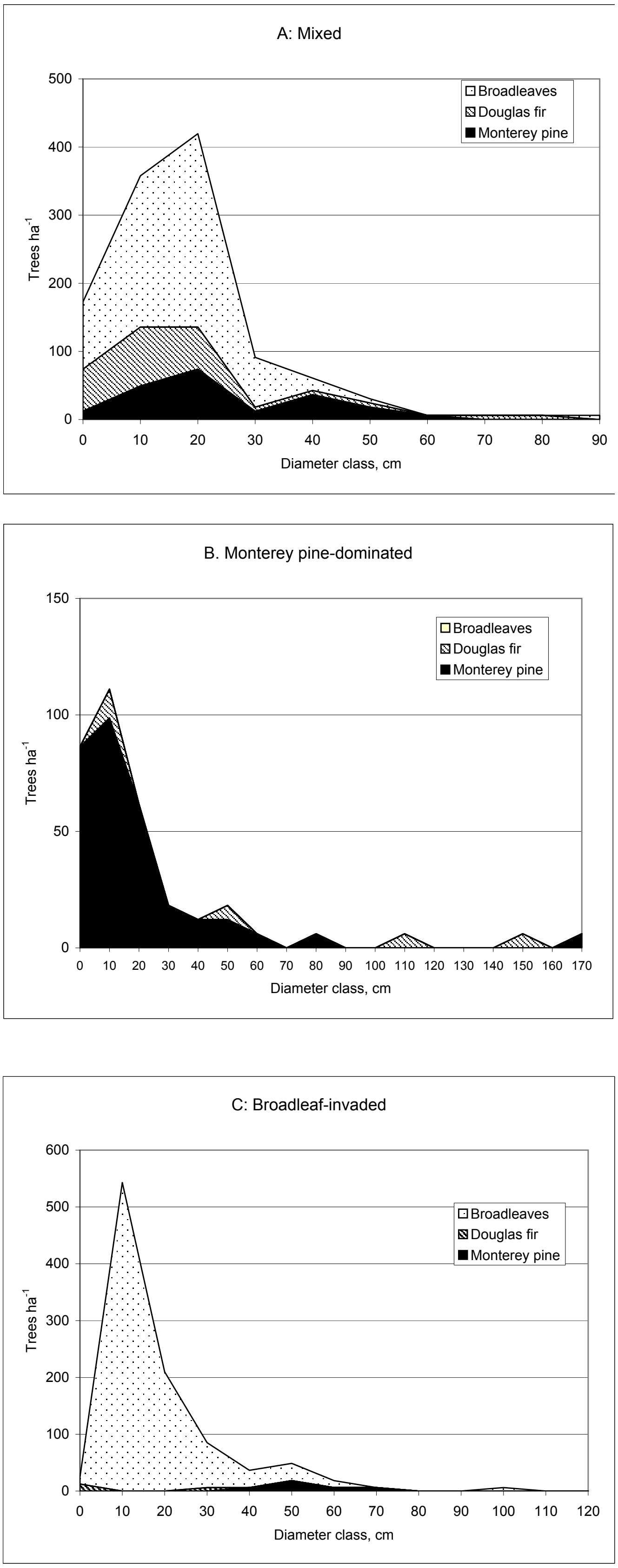

Figure 1. Examples of tree size and species distributions in native uneven-aged Monterey pine stands at Año Nuevo, California (Piirto and Valkonen 2005). Number and species category of trees by 10-cm diameter classes. A: Complex mixed-species structure. B: Almost pure Monterey pine. C: Broadleaf invaded.

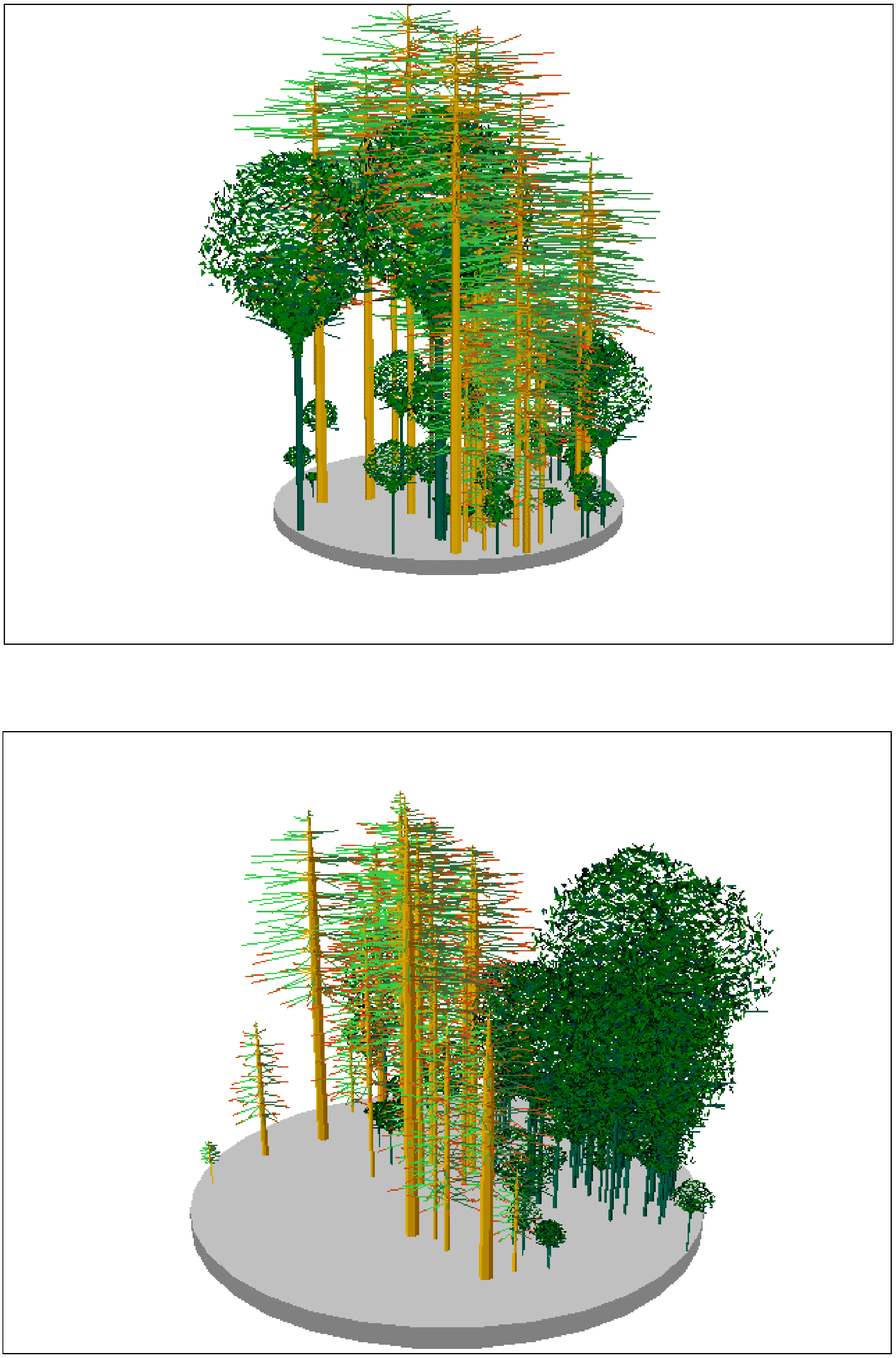

Figure 2. Examples of clearly different spatial distributions in terms of complex mixed-species diameter distributions as in Fig. 1A. Illustrations were produced with the Stand Visualization System by McGaughey (2001).

4 Regeneration

Regeneration is an essential component of the dynamics of structurally complex stands managed with continuous cover systems or regenerated naturally. In many cases, the emergence, survival, and vitality of advance regeneration of desirable species is a valuable asset in such stands. Its emergence and presence can be promoted in ways adapted according to the properties and requirements of the species.

In the Monterey pine study (Piirto and Valkonen 2005), a regeneration survey confirmed prior observations that the number of Monterey pine was critically low in the forest. The average number of seedlings and saplings was 45 ha^{-1}. Very few sample plots any Monterey pine regeneration at all (Auten 2000).

Although the result and the conclusion were clear in this case, one survey assessment is mostly not enough to reveal the dynamics of regeneration in complex stands, particularly when treatments are applied. Long-term monitoring on repeatedly measured sample plots is required. This is illustrated in Fig. 3. The number of Norway spruce seedlings constantly decreased in selection stands in southern Finland. A very abundant seed crop combined with a cool rainy summer resulted in plentiful regeneration in 1990. Average mortality and regeneration rates in the subsequent years then resulted in the decline. A single assessment at the beginning of the observation period would have yielded a grossly exaggerated perception of the regeneration potential in the stands.

Regeneration is most effectively surveyed on small plots distributed throughout the stand or plot area. They can be mapped for coordinates and used for spatial analysis and modeling together with the tree data. Additionally, the spatial distribution is also attended to at the same time. The number of empty (or stocked) plots is an essential parameter in addition to the total number of stems.

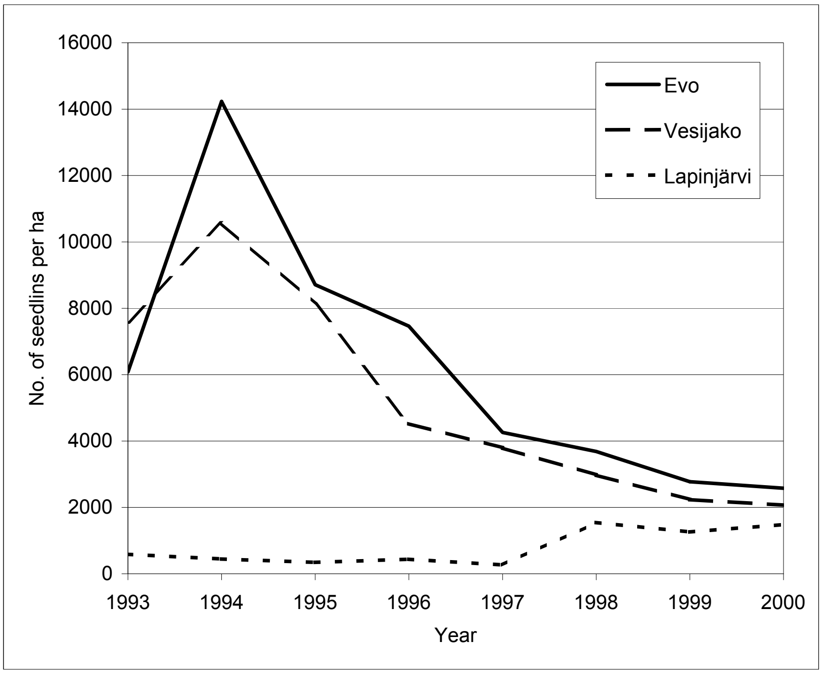

Figure 3. Average number of Norway spruce (Picea abies Karst) seedlings (height 3–10 cm) on the ERIKA sample plots in uneven-aged spruce stands in southern Finland in 1993–2000 (Ollikainen 2001).

5 Tree Growth

Knowledge on the growth of trees of different species and sizes, and other attributes controlled by stand density and structure, is essential to the manager of complex stands. It constitutes the basis for the selection of trees to remove for revenue and for the promotion of the retained trees.

Fig. 4 shows that the maximum diameter and basal area growth rate for Monterey pine was observed at about 60–90 cm. The largest trees grew very slowly in comparison. Stand density had a very remarkable influence on tree growth. It was concluded that in order to promote Monterey pine, stand densities should be substantially reduced from the current levels (average 50, maximum 70 m^2/ha^{-1}). In addition to remove trees of the undesirable species, some of the largest pine trees could be removed to maximally promote pine growth.

Diameter increment data can be reliably acquired in terms of temporary sample plots through coring – where the trees produce pronounced annual rings. For instance, increment of the broadleaves could not be measured in the absence of rings in the Monterey pine study, despite the fact that the conifers showed distinct annual rings caused by the variation of dry and wet seasons. That is a common obstacle in with tropical conditions and species. Studies with growth bands (Nöjd and Isango 2003, and article by Nöjd in this publication) can offer a solution but through arduous work only.

Tree height data would be useful in studies on stand dynamics, because mutual shading is closely correlated with height differences. However, height increment data is much more difficult to obtain than diameter increment data. Additionally, there is a strong correlation between tree diameter and height within a species that heights can be estimated with sample trees and models (h = f(d)) in most applications.

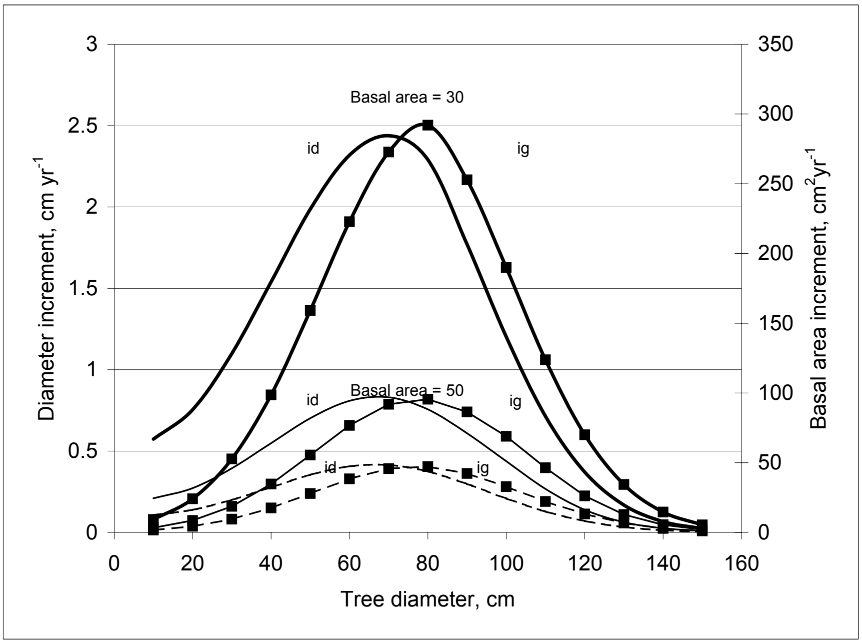

Figure 4. The effect of tree diameter and stand basal area on the diameter and basal area increment of Monterey pine trees (Piirto and Valkonen 2005). Stand basal area 30, 50, and 70 m^2ha^{-1}. id = diameter increment, ig = basal area increment.

6 Models

Modeling is a very useful way of extracting results and constructing tools from empirical data acquired from research plots. Empirical models are attempts to summarize the essentials factors of tree properties in terms of flexible sets of functions with statistically estimated parameters. Tree growth prediction is the key component in most applications. Generally, tree growth can be consistently and rather comprehensively predicted with a few basic types of variables: species, tree size (e.g. diameter), site productivity (site index or some classification), and competition for resources and growing space (e.g. stand density or individual tree level competition measures).

Tree growth according to tree size generally follows an inherent growth rhythm where small trees rapidly enlarge their metabolic (photosynthesizing) structures and accelerate growth. As their catabolically active structures inevitably expand at an increasing rate, the increment rate culminates at some point, and a decreasing development begins. This is clearly illustrated in Fig. 4. In model notation, this development can be described with two basic components:

$$\ln(i_g) = b_0 + b_1 d - b_2 d^2$$

Where
i_g = increment of tree basal area
d = tree diameter
$b_{i,\ i=1,n}$ = estimated parameters

ln transformation is often applied to as required case by case, i.e. here in the Monterey pine study (Piirto and Valkonen 2005).

Competition can be described with stand-level parameters (often basal area), or tree level competition measures, or a combination of both:

$$\ln(i_g) = b_0 + b_1 d - b_2 d^2 - b_3 G - b_4 CI$$

Where
G = stand basal area
CI = competition index

A multitude of tree-level competition index formulations is available in research papers. Basically, they attempt to describe the competition pressure that each individual tree is subjected through the presence of other trees in its vicinity. The indexes can be distance-dependent or distance-independent. Basically, a distance-dependent competition index is based on the principle that another tree causes a competition influence that is directly proportional to its size and distance from the subject tree like the very basic formulation of Hegyi (1974) as modified by Biging and Dobbertin (1992) and applied in Piirto and Valkonen (2005):

$$CI_{jm} = \sum_{j \neq m} d_m / d_j \left(s_{jm} + 1\right)$$

Where
CI = competition index for subject tree j, including competitors m
d_j = diameter of subject tree j
d_m = diameter of competitor tree m
s_{jm} = Distance from tree j to tree m

With such a simple formulation and parameters estimated with data from a set of temporary sample plots, results highly relevant to practitioners were produced in the Monterey pine study (Piirto and Valkonen 2005). In the absence of site index curves and applicable site classification systems, site was taken into account with stand-level random parameters. Secondary models were constructed for the prediction of tree height and crown width for illustration purposes. Separate models were constructed for each of the conifer species. As increment data could not be acquired for broadleaves through coring, their increment was predicted with the pine models. To estimate the potential influence of uncertainty in that prediction, sensitivity analyses were performed.

7 Treatments and Simulations

The constructed models can be used to examine various aspects of stand dynamics involving tree growth. Stand development subject to relevant treatments is an obvious application. In the Monterey pine study (Piirto and Valkonen 2005), the models were used to assess the potential benefits of treatment alternatives in the promotion of Monterey pine in the stands. The following treatments were applied to each sample plot:

1. No treatment
2. Group selection: Circular gaps of 24 m diameter (0.045 ha), where all trees were removed, except that small ($d \leq 25$ cm) conifers were retained. The purpose was to promote the growth of small pines and to initiate regeneration.
3. Single tree selection. Some (5–25 ha^{-1}) of the largest ($d > 60$ cm) trees were first removed, then a proportion of the large broadleaves was removed until the same plot basal area was achieved as was established in the gap treatment on that plot. The purpose was to promote existing Monterey pines with the highest growth potential (mid-sized), and to establish more favorable conditions for small pines, pine advance growth, and regeneration.

Fig. 5 illustrates an example of the treatments on one plot. The development of the stand on each plot in each alternative was then simulated for 20 years (i.e. for about one cutting cycle). There was no way to predict regeneration, and its role was ignored. Tree mortality was applied as an empirically defined maximum basal area limit (70 m^2/ha) with random mortality weighted by species.

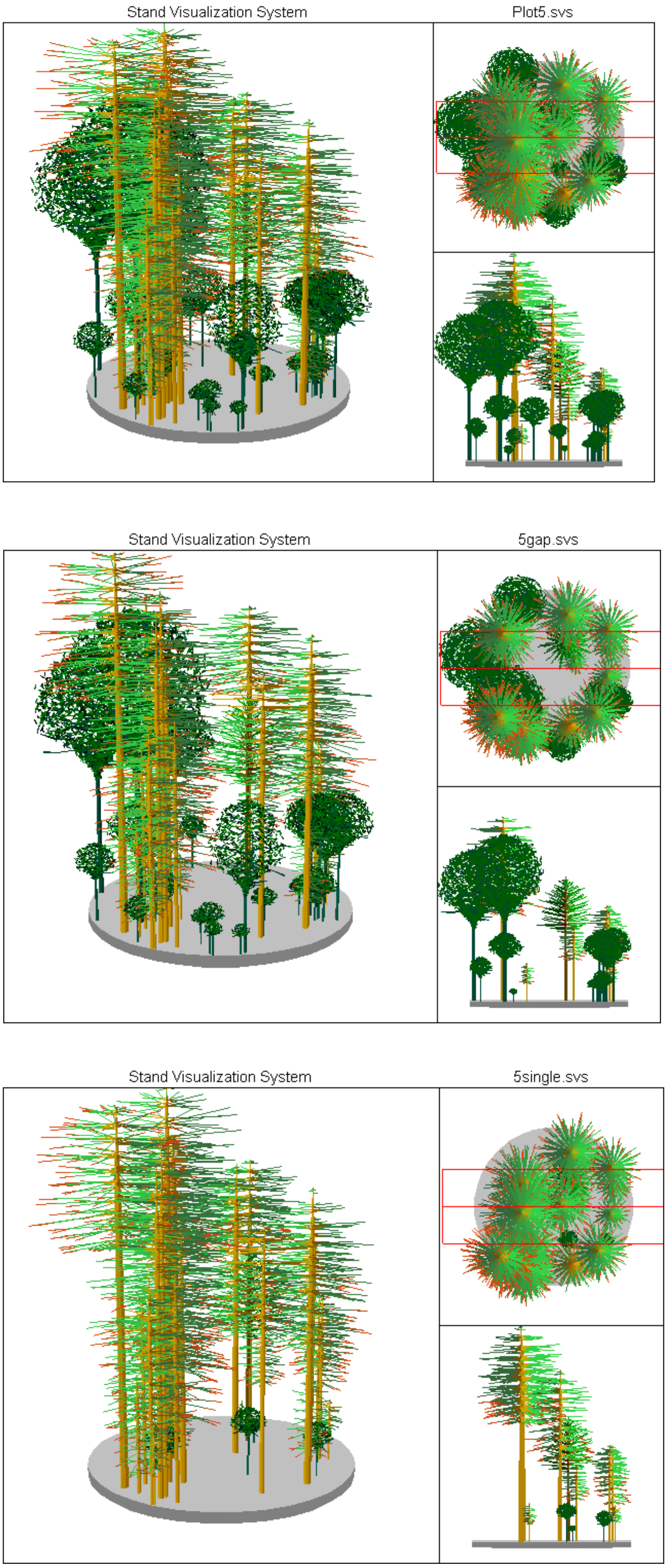

Figure 5. Examples of the treatments on one plot. A: No treatment: B: Group selection. C: Single tree selection. (Piirto and Valkonen 2005). Illustrations with the SVS system by McGaughey (2001).

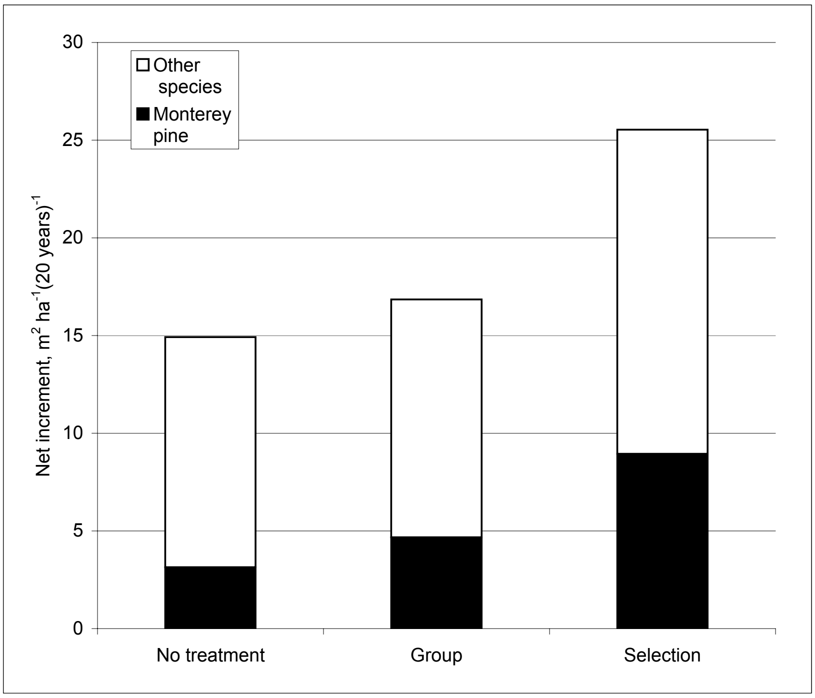

Figure 6. Net basal area increment by treatments and species groups for the 20-year simulation period (Piirto and Valkonen 2005).

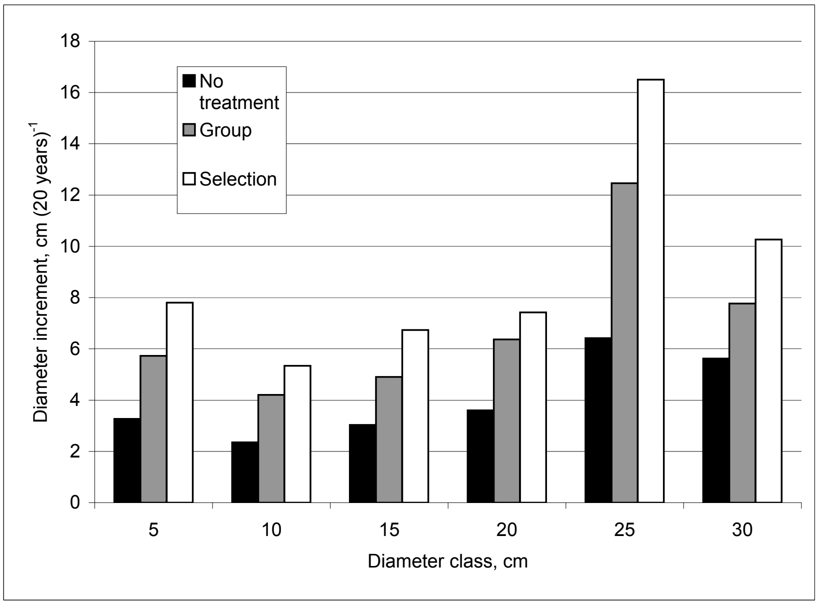

Figure 7. Average diameter increment of small Monterey pine trees by 5-cm diameter classes during the 20-year simulation period by treatments (Piirto and Valkonen 2005).

The basic results in Figs 6 and 7 indicated that group or single tree selection treatments are urgently required to promote Monterey pine in the stands. Single tree selection seemed a little more beneficial to Monterey pine than the group selection treatment. However, the analyses comprised the development of those trees already present in the stands, ignoring regeneration. Given the shade intolerance of Monterey pine, treatments with larger gaps may tend to be more efficient than single-tree or group selection in promoting regeneration. The most effective ways to promote regeneration will be an essential component of optimal treatments, given the critical lack of regeneration in the stands. Regeneration trials with various gap sizes and soil treatments were then initiated in the forests.

8 Conclusions for Analysis on Miombo Stands

The methodology applied in the Monterey pine study (Piirto and Valkonen 2005) must be modified to be applicable to analyses on miombo stands. That study was based on temporary plots, where tree increment data was acquired by coring. Very likely, that is currently not feasible with miombo species. Knowledge and experience on the formation of annual rings is almost totally lacking for them. Consequently, the plots must be at least semi-permanent with the measurements repeated at one-year intervals for at least a few years (3–5) to account for possible variations between years (if any). Of course, even a one-year observation period can yield data for rough initial estimates, but the results may be severely biased if tree increment for that year deviates markedly from the average due to weather conditions or other factors. Tree diameters must be measured with high accuracy to provide high-quality increment data. Growth bands may be useful.

The very large array of species makes the acquisition of relevant tree increment data applicable for general analysis and modeling a much more arduous effort than in mid-latitude forests. A number of observations are required to cover the range of variation of each variable in the model. The ecological and physiological properties and different growth patterns of trees add a multiplicative dimension to the task. Species may be aggregated into groups with more or less similar growth responses, for which a firm basis can be gradually established through accumulation of data and experience.

If accurate tree increment data can be successfully combined with an appropriate measures of competition (i.e. description of how different kinds of trees influence each other), modeling is a very powerful tool in describing the dynamics of stands with complex structures. The basic competition measures should account at least for stand density and tree size distribution. The utilization of spatial indexes is often beneficial, but not necessary. A multitude of different types and formulations of indexes is available for the enterprising researcher to explore and experiment with. A serious problem of the approach is that the evaluation of index performance and reliability of estimates is inherently very difficult (Ojansuu 1995) For instance, basal area of trees larger than the subject tree has often been a very good parameter which takes the relative dominance of trees into account in addition to stand density (Schütz 2001, 2006).

The establishment of regeneration must be accounted for in management systems based on partial cuttings and natural regeneration. Additionally, the development of regeneration, natural or artificial, must be described for any kind of system. The examples given above suffice to demonstrate that long-term observation of the dynamics of regeneration and the factors behind the developments is necessary for reliable prediction and action in practice. Treatments can be applied only when the basic features of the regeneration process are understood. That said, it is understandable that regeneration studies in miombo woodlands are far more intricate than for other types of environments: fires, herbivory, sprout and coppice regeneration, multitude of species, grass and grazing, and climatic and edaphic variations constitute a complex web of interactions which is very difficult to assess and manipulate for desired results.

Simulation with models constructed with empirical data can constitute very powerful tools for forest managers when the data basis is comprehensive (e.g. the Motti simulator in Finland; http://www.metla.fi/metinfo/motti/menu-esittely-en.htm). Simulators with limited data can also be interesting to researchers and practitioners for gaining a preliminary insight to stand structure and dynamics, basic management alternatives and their consequences in a flexible, computerized setting: Users must be made aware of the limitations of the models and the system as a whole – the constructor bears the responsibility for that. In the miombo environment, the type of forest management and silviculture that may optimally promote the goals of the various stakeholders in a specific situation is an extremely complex question, with equally variable applications as solutions. In terms of such a small-scale project as MITMIOMBO, we can only address one or two basic treatment principles on the experimental, leaving a large variety of alternatives aside. But it is not the specific treatments that are on trial and display, but principles and approaches, of which empirical modeling seems one of the most powerful ones despite the formidable challenges.

References

Auten, S. 2000. Continuous Forest Inventory for Swanton Pacific Ranch-Scott's Creek Management Unit. Natural Resources Management Department, California Polytechnic State University, San Luis Obispo, California. 27 p. + 2 app.

Biging, G. & Dobbertin, M. 1992. A comparison of distance-dependent competition measures for height and basal area growth of individual conifer trees. Forest Science 38: 695–720.

Campbell, B. (ed.). 1996. The Miombo in transition: Woodlands and welfare in Africa. CIFOR, Bogor, Indonesia. 266 p.

Chidumayo, E. & Frost, P. 1996. Population biology of miombo trees. In: Campbell, B. (ed.). The miombo in transition: Woodlands and welfare in Africa. CIFOR, Bogor, Indonesia. p. 59-71.

Hegyi, F. 1974. A simulation model for managing jack-pine stands. In: Fries, J. (ed.). Growth models for tree and stand simulation. Research Notes. Royal College of Forestry, Department of Forest Yield Research, Stockholm, Sweden. p. 74-90.

McGaughey, R. 2001. Stand Visualization System, Version 3.30. Manual for the public domain software. USDA Forest Service, Pacific Northwest Research Station, Seattle, Washington. 141 p.

Musokonyi, C. 1998. Research on indigenous tree species in Zimbabwe: A summary of major activities and their outcomes. In: Pukkala, T. & Eerikäinen, K. (eds.). Modeling the growth of tree plantations and agroforestry systems in south and east Africa. University of Joensuu, Faculty of Forestry, Research Notes 80: 221–234.

Nöjd, P. & Isango, J. 2003. Growth periodicity of Pinus patula in Southern Tanzania. Journal of Tropical Forest Science 15(1): 352–358.

Ojansuu, R. 1995. The ability of competition indices to describe stand dynamics. In: IUFRO XX World Congress, Abstracts of Invitated Papers. p. 287.

Ollikainen, H. 2001. Regeneration of uneven-aged Norway spruce stands in Southern Finland. Metsätalou–den koulutusyksikkö. Mikkelin ammattikorkeakoulu, Pieksämäki. 37 p. (In Finnish with English summary).

Piirto, D. & Valkonen, S. 2005. Structure and development of pitch canker infected Monterey pine stands at Año Nuevo, California. Forest Ecology and Management 213: 160–174.

Pukkala, T. & Eerikäinen, K. (eds.). 1998. Tree seedling production and management of plantation forests. Proceedings of the meeting in Tanzania, 3–10 November, 1997. University of Joensuu, Faculty of Forestry, Research Notes 68. 182 p.

Schütz, J. 2001. Der Plenterwald und weitere Formen strukturierter und gemischter Wälder. Parey Buchverlag, Berlin. 207 p.

Schütz, J. 2006. Modelling the demographic sustainability of pure beech plenter forests in Eastern Germany. Annals of Forest Science 63(1): 93–100.

Valkonen, S., Isango, J., Mabvurira, D., Muchiri, M. & Saramäki, J. 2000. A review of growth and yield models for plantation forests in eastern and southern Africa. University of Joensuu, Faculty of Forestry, Research Notes 114. 59 p.