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Identification of boreal mixedwood forest structure cohorts in Northwestern Ontario using Ontario's forest resource inventory, Abitibi-Bowater's continuous forest inventory and stepwise discriminant function analysis

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**Identification of Boreal Mixedwood Forest Structure Cohorts in
Northwestern Ontario using Ontario's Forest Resource Inventory,
Abitibi-Bowater's Continuous Forest Inventory and Stepwise
Discriminant Function Analysis**

by

Gareth Davies

A Graduate Thesis Submitted

in Partial Fulfillment of the Requirements for

the Degree of Master of Science in Forestry.

Faculty of Forestry and the Forest Environment

Lakehead University

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ABSTRACT

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A model was developed to determine if Ontario's Forest Resource Inventory (FRI) could be used to classify boreal mixedwood stands in northwestern Ontario into structural cohorts as proposed in the Multi Cohort Forest Management (MCFM) concept. Successful methods developed to-date for determining cohort status rely on Weibull functions of tree diameter distributions. This study proposed an alternative method for multi-cohort classification based on the range of stand attributes found in the FRI. Weibull classified stands were analysed using FRI data to determine if a new model of cohort classification was possible. Results from this analysis showed that FRI data alone were insufficient to predict cohort status. An analysis was subsequently conducted using the richer data set found in the Continuous Forest Inventory (CFI). Stepwise discriminant function analysis of the CFI data revealed three diameter based variables capable of significantly discriminating between cohorts: Diameter Class Richness, Coefficient of Variation and Evenness. The model built using CFI data correctly classified mixedwood stands into the cohort classes in 75% of the cases. Validation tests of this predictive model using Permanent Sample Plot (PSP) data revealed the model capable of discriminating between the Cohorts in 79.2% of the cases. The model was able to successfully classify Cohort 1 and Cohort 2 stands, but was less able to classify Cohort 3 stands. Model accuracy was improved when a two-cohort approach was applied, using Cohort 1 (even-aged cohort) and a combination of Cohorts 2 and 3 (complex structured cohort). This study shows that diameter class data is essential in predicting cohort class in boreal mixedwood stands.

Key Words: mixedwoods, boreal, cohorts, multi cohort forest management, Weibull functions, diameters, discriminant function analysis.

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1. INTRODUCTION

1.1 STUDY PROBLEM

Past silvicultural practices have often led to natural boreal mixedwoods being clearcut with the intention of converting managed areas to single species plantations. This approach has not met with a great deal of success in northwestern Ontario and, without intensive efforts to limit competition, the resulting regeneration tends to be dominated by balsam fir (*Abies balsamea* (L.) Mill.) or trembling aspen (*Populus tremuloides* Michx.) (Wedeles *et al.* 1995). There are many reasons to manage these sites as mixedwoods (e.g. protection from the loss of ecosystem diversity, habitat and resilience) and to retain them in the forested landscape (Lieffers and Beck 1994).

Ontario requires that forest management practices on Crown forests imitate natural disturbance patterns for the purposes of preserving ecosystem resilience and integrity, and minimising ecosystem disruption (OMNR 2001). The Natural Disturbance Pattern Emulation Guidelines and, more recently, the Landscape Guide, stress the requirement to emulate natural patterns across the landscape with little emphasis placed upon structure (e.g., age class distribution and cohort representation) and composition (OMNR 2009). Although the range of effects of conventional forms of harvesting on ecosystem resilience, process and function are fundamentally different from those caused by natural disturbances in forests, forest management practices can be adapted to reproduce specific elements of the natural disturbance regime found within this range (Perry 1998). Ontario's Forest Resource Inventory (FRI), which forms the

basis for all Ontario Forest Unit management plans, did not, until recently, provide forest structural or attribute information. Some Forest Management Units will rely on these FRIs, which lack stand structural attributes, for the next 10 years of management.

Natural disturbance based forest management (NDBFM) supports the retention and development of ecosystem features in managed forests which are similar to those caused by natural disturbances (Attiwill 1994). This involves the preservation of stand scale physical and ecological artefacts through appropriate silviculture (Franklin *et al.* 2002; Harvey *et al.* 2002), and the landscape scale reproduction of structures and compositions comparable to the effects of the prevailing local disturbance regime (Franklin 1993b; Bergeron *et al.* 1999b; Bergeron *et al.* 2006). Conversely, the effects of past management practices have caused a reduction in the range of landscape level compositions and the formation of structural artefacts for which there are no ecological equivalents (Messier and Kneeshaw 1999).

The Multi Cohort Forest Management (MCFM) concept proposed by Bergeron *et al.* (1999a; 1999b) allows for the emulation of natural structural and temporal attributes within managed forest stands through the application of silvicultural practices as an alternative to clearcutting, such as modified clearcut, shelterwood or selection harvesting. In addition, these alternative silvicultural systems enable old growth forest structures, which would otherwise be removed from the forest under clearcut systems, to be represented on the landscape without relying exclusively on harvest deferrals or extended rotations.

Specifically, Bergeron *et al.* (1999a) propose a system whereby some managed stands would be clearcut and then artificially regenerated (e.g., by planting or seeding)

in order to simulate the effect of stand replacing fires. The even-aged stands resulting from this treatment would represent the first cohort of the three cohort system. Other managed stands would be subject to a partial harvest which would simulate natural aging and development into two storied, mature stands. A final group of stands would be managed through a selection harvest in order to replicate the natural gap dynamic phase of old growth stands. Not all stands in a forest would be managed in this way. The purpose of MCFM is to allow for selected areas to be withdrawn from the normal harvest rotation in order to maintain a representative sample of age class structures across the landscape through alternative silviculture. The proportion of stands managed in this fashion should reflect the natural disturbance cycles across the landscape (Bergeron *et al.* 1999a). This definition of cohort as described by Bergeron is the will e used throughout this study.

In order to apply a MCFM approach, the land base must first be classified by forest structure and cohort type. This provides a baseline status from which to derive future desirable forest conditions. The baseline cohort status describes the current condition of the forest but is less definite about describing the processes that shaped its development. A full, historical record of the natural disturbance regime, past harvesting practices, management regimes, climate variances, soil characteristics and geology across the landscape would provide more detail into the development of the current cohort structure and its future trajectory (Attiwill 1994; Bergeron and Harvey 1997).

Presented within this thesis is a cohort selection model for mixedwood stands in the Dog River-Matawin Forest of north western Ontario. The model takes the form of a Discriminant Function Analysis of stand structural attributes and diameter distributions.

The intent is to determine the specific stand structural components necessary to classify boreal mixedwood stands into cohorts. The purpose is to aid operational decisions and forecasting in forest management planning.

1.2 STUDY OBJECTIVE, OUTLINE AND LIMITATIONS

The Dog River-Matawin Forest 2005 Forest Management Plan contained a preliminary analysis of a new type of forest resource inventory: the Continuous Forest Inventory (CFI). This analysis revealed that a high proportion of the forest had structures which were more complex than would be found in even-aged stands. However, the analysis was unable to spatially identify the complex structured stands within the greater forest. It was reasoned that if the stand attributes contained within the FRI (species, height, age, site class and stocking) could be linked to a cohort type derived from the CFI, then the stands could be spatially located within the forest, and a map of complex structured stands could be developed. The CFI, as used in Europe and America, places more importance on “where the stands are” as opposed to “how much wood is there”. The primary objective of this study is to link these two aspects to determine if Ontario’s existing FRI can be used to classify mixedwood stands into structured cohorts as an aid to operational planning.

The methods developed to-date for determining the cohort status of forest stands rely on deriving Weibull functions of diameter distributions of the trees found within the stands (Kuttner 2007). The resulting histogram of diameter distributions is visually interpreted with reference to the Weibull Shape and Weibull Scale of the curve to assign a stand to one of the three cohort categories allowed in the MCFM model. The thorough

list of diameter distributions required for this method, though producing an accurate cohort classification, entails operationally cruising stands selected for harvest allocations. This study proposes to develop an alternate method for multi-cohort classification based more on a range of stand structural attributes and less on a single characteristic such as diameter distribution. FRIs which contain a range of structural attributes (species composition, tree height, tree age, stand stocking and site class) exist for most managed forests within Ontario. By using known, Weibull classified stands as a benchmark, and deriving classifications from the range of attributes found in the FRI, we can compare the two and determine if a new model of MCFM classification is possible.

The CFI incorporates both diameter distribution data and a range of other stand structural data (e.g. snags, basal area, forest ecosystem classification). From the diameter distribution data, a Weibull cohort status can be established for each of the CFI plots. A subsequent examination of a range of structural attributes contained within each stand can be used to create a model that predicts cohort status. A determination of the accuracy of the new model can be made by determining its level of agreement with the Weibull classification.

Additionally, Permanent Sample Plot (PSP) data collected by the Ontario Ministry of Natural Resources, which includes diameter distributions along with other stand structural data, is also available for this forest. This data will be used to test the validity of any model which has been created from the FRI or CFI.

This thesis describes a previously untried method of multi-cohort classification. Other studies have focussed on the black spruce-moss forests of Quebec (Boucher *et al.*

2003), the boreal forest of northwestern Quebec (Bergeron *et al.* 2002) and the boreal forests of northeastern Ontario (Kuttner 2007) to develop, refine or apply the MCFM concept. This study differs from previous ones in that it: a) focuses exclusively on the mixedwood component of the boreal forest; b) extends the technique westward from Quebec and northeastern Ontario to the boreal regions of northwestern Ontario; and c) compares two MCFM classification methods (Weibull diameter distribution and non-Weibull structural attribute) to determine if the new model is comparable to the existing one.

The tree diameter data obtained from the CFI database will form the basis for the cohort classification of the stands analysed in the study. Using the established Weibull function method, each stand will be assigned a cohort (the Weibull cohort). Discriminant Function Analysis (DFA) will then be used to examine the stand attributes found in the FRI dataset that corresponds to each of the Weibull cohort classified stands. This will allow a non-Weibull cohort classification to be derived for each stand (based on FRI data), which can be compared to the Weibull cohort classification. This DFA Cohort classification will be repeated using the stand attributes found in the CFI dataset to derive a non-Weibull cohort classification for each stand (based on CFI data), which can be compared to the Weibull cohort classification. Finally, any models that successfully predict cohort status based on non-Weibull data will be tested against Weibull classified PSP plots to gauge model predictive accuracy.

The Literature Review explores the theory of natural disturbance based forest management (NDBFM), with particular emphasis on alternative silvicultural systems and the development of the Multi-Cohort Forest Management (MCFM) concept. It also

investigates the cohort classification techniques developed in northwestern Quebec by Bergeron (Bergeron *et al.* 2002), Boucher (Boucher *et al.* 2003), Groot (Groot *et al.* 2004b) and Harvey (Harvey *et al.* 2002) and the further refinements for northeastern Ontario proposed by Kuttner (2007). The Materials and Methods section describes the process of using Weibull Functions derived from diameter distributions to classify the mixedwood component of the Dog River-Matawin Forest (DRMF) into cohorts. It also explains the procedures used in Discriminant Function Analysis and provides information about the three data sets (FRI, CFI and PSP) used in the analysis. The Results section displays the results of the multivariate analyses of FRI and CFI data sets, the equations used in the developed model, and the results of the test of model validity using the PSP data set. The Discussion section outlines and discusses the findings as well as their significance. The Conclusion highlights the pertinent findings and suggests further refinements to improve model reliability and accuracy.

This study relied on the use of external data sets. The amount of data collected, and the time and cost involved in its collection, are prohibitive within the time frame of a Master's degree. The data was collected by qualified members of external agencies and generously shared for the purpose of this study.

2. LITERATURE REVIEW

2.1 BOREAL MIXEDWOODS OF EASTERN CANADA

The boundary between the southern portions of the boreal forest and the northern regions of the temperate forest is not a sharp one; it is a transition zone which produces a rich variety of mixedwoods (Apps *et al.* 1993). The naturally occurring, boreal mixedwood stands of eastern Canada are often dominated by trembling aspen or paper birch (*Betula papyrifera* Marsh.) in early succession, black spruce (*Picea mariana* (Mill.) BSP) or white spruce (*Picea glauca* (Moench) Voss) in mid-succession, and balsam fir in late succession, although any of these boreal species can be present throughout the duration of stand development (McCune and Allen 1985; MacDonald 1995; Lieffers *et al.* 1996). These are the five most commonly found over-story species in the naturally occurring boreal mixedwoods of northern Ontario (Wedeles *et al.* 1995).

The structural, compositional and spatial patterns of boreal mixedwoods are shaped by the combined pressures of disturbance, succession and environment. The principal natural instruments of disturbance in the boreal forests of eastern Canada are stand replacing fire, wind-throw, insects and pathogens (Frelich and Reich 1995; Bergeron *et al.* 2001; James *et al.* 2007). The range of patterns found in boreal mixedwoods today was produced by repeated stand and landscape level disturbances which “reset” stand level succession to earlier conditions (Bergeron *et al.* 1999a). Current boreal mixedwood stand compositions and structures are a product of the nature of any stand altering disturbances (e.g., fire, blow-down, insect or pathogen damage),

any previous management interventions (e.g., harvesting or stand improvement activities), the pre-disturbance stand composition (e.g., single species, mixedwood), the subsequent regeneration of the stands (e.g., competition, seed sources, vegetative or artificial regeneration), and the environmental conditions affecting post disturbance succession (e.g., climate, landform, etc.) (Oliver and Larson 1996; Drever *et al.* 2006).

Mixedwoods are by definition composed of combinations of two or more species, so conversion of mixedwoods to single species stands corresponds to a loss of tree alpha diversity (Sarkar and Margules 2002; Hooper *et al.* 2005; Scholes and Biggs 2005). Mixedwoods may also support more varied stand structures and wildlife habitats than single species stands (Hansen *et al.* 1991; Hobson and Bayne 2000; Chen and Popadiouk 2002; Ishii *et al.* 2004) and they may be more resistant (able to absorb change) and resilient (capable of returning to a given state after disruption) to natural disturbances (Su *et al.* 1996; Niemela 1999; Cumming 2001). Retaining components of structure and composition as artefacts within partially harvested mixedwood stands also allows for the retention of elements of the pre-harvest condition (e.g., genetics, composition and structure) which are essential for the post-harvest regeneration of the stand to a mixedwood condition (Frelich and Reich 1995; 1999), and for the reduced distinction between disturbed and intact stands (Hansen *et al.* 1991). If partial harvesting can be adapted to leave behind similar legacies, then these new harvesting techniques might be better able to approximate natural patterns (Lee *et al.* 1997) and lessen the impact caused by tree removal (Merrill *et al.* 1998; Schieck and Hobson 2000).

Boreal mixedwoods can be more difficult to manage than single species stands due to the intricacies involved in balancing the silvicultural needs, growth patterns, regeneration characteristics and rotation lengths of the constituent species with the need to achieve a sufficient amount of wood volume (m^3/ha) from these generally lower yielding stands (Lieffers and Beck 1994). As noted above, this complexity has often led to the employment of management practices which encourage the development of monocultures at the expense of boreal mixedwoods, “unmixing the mixedwoods” (Man and Lieffers 1999; Hobson and Bayne 2000), with the purpose of reducing silvicultural costs while increasing both the productivity and profitability of the stands. Any productivity gains which are achieved by monocultures, however, often come at the expense of biodiversity and structural diversity within the managed landscape (McElhinny *et al.* 2005).

2.2 NATURAL DISTURBANCE BASED FOREST MANAGEMENT

“Asking the right questions is as important as answering them” (Cooperrider 1996). In the context of Natural Disturbance Based Forest Management (NDBFM), many questions surround the type of “natural” vegetation to be maintained and the class of “natural” disturbance to be mimicked in order to achieve management objectives (Niemela 1999). There is no clearly accepted definition of a natural disturbance regime. One group holds that natural disturbance regimes must be viewed without reference to any particular, arbitrary reference state (e.g., pre-industrial, pre-colonisation or pre-settlement forest composition). Those who hold this view deem disturbance regimes to be “a moving target”, especially in the face of climate change (Hunter 1996). They

advocate management practices that are designed to move ecosystems closer to their natural structure and function, into a state without human influence. However, others hold that there is "...no way of specifying the features of a disturbance regime except when both location and time are fixed". They argue that a disturbance regime refers to the "temporal and spatial pattern of a particular type of event" (Haila 1997; Comer 1997) and that there is no way to know what an ecosystem would look like without human influence. This position leads to the development of natural benchmarks based on a specified time and region.

NDBFM favours the development of stand and landscape compositions and structures which are similar to natural ecosystems, in order to emulate biodiversity and ecological function relative to a natural reference state (Franklin 1993b; Bergeron *et al.* 2002). The fundamental assumptions of NDBFM are that ecosystems are already adapted to the range of the prevailing natural disturbance regimes, and that structural and functional elements, essential to ecosystem development and maintenance, are already preserved within this range (Long 1998; Niemela 1999). Therefore, management practices that generate patterns and structures resembling those created by the historic disturbance regime should allow the forest ecosystem to tolerate and absorb the associated ecological changes, without being fundamentally changed themselves (Drever *et al.* 2006; Delong 2007).

Forest management systems that are based on the dominant natural disturbance regime within the landscape can maintain ecological resilience and retain important ecosystem functions by preserving the diverse variety of age classes, biodiversity and habitats found in natural, unmanaged forests (Walker *et al.* 2004; Drever *et al.* 2006).

There may also be economic advantages to management practices that are closely related to natural ecosystem dynamics (e.g., reduced regeneration and tending costs) (Lieffers and Beck 1994; Ruel *et al.* 2007). However, the stand and landscape level effects of conventional forms of harvesting are fundamentally different from those caused by natural forest disturbances. For example, the rotation periods of harvests tend to be shorter than the natural disturbance cycle which results in fewer old growth stands in the managed condition than would be found in the natural state (Wallin *et al.* 1996); and conventional harvesting can only partially replicate the wide variety of conditions produced by natural disturbance (Hansen *et al.* 1991). Conversely, “it is probably impossible and potentially undesirable” for us to fully copy nature because the emulation of extreme disturbance events would lead to clearcutting thousands of square kilometres of forested land (Messier and Kneeshaw 1999).

The silvicultural systems employed in NDBFM attempt to reproduce some, but not all, of the specific elements created by the prevailing natural disturbance regime. However, there are important distinctions between a natural forest disturbance and its correlated silvicultural system. For example, group selection cutting is a silvicultural practice that resembles the natural mortality caused by wind-throw in a mixedwood forest. However, group selection does not result in the exposure of the mineral soil that occurs when wind-thrown trees are uprooted. The absence of exposed mineral soil may result in a lack of seedbeds and may curb the regeneration of certain species. This may result in a shift in dominance to species relying more on vegetative regeneration (Bergeron *et al.* 1999b). Other effects which may not be successfully reproduced by silviculture include: soil conditions (e.g., compaction, nutrient cycling, fertility,

moisture content and pH); a lack of snags, litter and downed woody debris; the regeneration of species with serotinous cones; and effects on long term productivity (Brais *et al.* 1995; Bergeron *et al.* 1999b).

In contrast to the common practice of species focussed conservation, the ecosystem and landscape level focus of NDBFM allows for the inclusion of a larger number of species, as well as the retention of their associated habitats. Forest management policies and guidelines in northern Ontario have tended to focus management efforts on creating conditions that would favour individual “umbrella” species (e.g., caribou, martin and other charismatic mega-fauna). However, preservation of species cannot be accomplished without a corresponding preservation of habitat, which includes structure as well as composition. The complex structures (e.g., spatial patterns, dead standing trees, downed woody debris) found in the different stand developmental stages enhance overall biodiversity, wildlife habitat and ecosystem function (Franklin *et al.* 2002).

2.3 ALTERNATIVE SILVICULTURAL SYSTEMS

Traditional methods of harvesting even-aged stands may not be suitable when dealing with multi-cohort, uneven-aged boreal mixedwoods, which may have lower stocking and volumes, and a greater need for careful logging around advanced regeneration.

Common silvicultural systems are often not applicable to natural ecosystem dynamics in that they initiate a repeated rotation of unchanging stand compositions (through intensive silviculture such as artificial regeneration or chemical control of competing vegetation), as compared to the gradual conversion of stand types, compositions and

ages found in natural, unmanaged forests (Bergeron and Harvey 1997; Niemela 1999; Drever *et al.* 2006). They may also produce stand conditions which do not resemble those which are found during the natural development of boreal mixedwoods (e.g., the action of stand disturbing fire on soil, the decay of downed woody debris over extended periods, the stratification resulting from the combined action of insect attack and blow-down). However, the range of diversity found in these developmental processes permits a corresponding range of methods that may be employed to partially replicate many of the structures found in naturally developed boreal mixedwoods (Wedeles *et al.* 1995).

Recent forest management practices have relied mainly on clearcutting followed by the regeneration of the site to an even-aged condition, through natural or artificial means. There is a strong negative public perception that clearcutting is the complete removal of all trees from a site (Bliss 2000). However, there are several distinct variations of the clearcut system. A commercial clearcut involves the removal of all commercially merchantable timber from a site (Davidson *et al.* 1988), leaving some standing, non-merchantable trees remaining. In contrast, a silvicultural clearcut incorporates renewal considerations into the operation, as can be seen from the definition provided by Forestry Canada (1992): “new seedlings become established in fully exposed microenvironments after removal of most or all of the existing trees.” Other variations of clearcutting include the seed tree system, which leaves some higher quality trees behind to act as a pre-adapted seed source for regeneration, and the shelterwood system, which offers a seed source and a degree of shelter and protection to the regenerating understory (Forestry Canada 1992).

The application of silvicultural systems (e.g., modified clearcut, shelterwood, partial and selection harvesting) as an alternative to clear-cutting enables old growth forest structures to be created and preserved in the landscape, thereby reducing the need for harvest deferrals or extended harvest rotations. The forest cover has become younger and more even-aged in some regions of the managed boreal forest as rotation periods have shortened in response to the demands of modern silvicultural practices. This abridgement of age classes has altered the forest stand and landscape level diversity and the associated wildlife habitat (Hobson and Bayne 2000; Drapeau *et al.* 2003).

Species succession within stands across the forested landscape is fundamental to the preservation of biodiversity and continuing productivity within boreal mixedwood ecosystems. Silvicultural systems that most closely resemble forest disturbances, with dynamics and effects comparable to those of natural origin, need to be considered when managing boreal mixedwoods (Bergeron and Harvey 1997). There is a continuum of available harvesting techniques, ranging from clearcutting and even-aged schemes to selection and uneven-aged schemes, that can be used in NDBFM (Franklin 1993a; Oliver and Larson 1996). Silvicultural systems that imitate ecosystem dynamics (e.g., species succession, gap dynamics) need to be employed with the aim of preserving as much of the natural biological diversity as is feasible (Haeussler *et al.* 2004).

Biodiversity in plant and wildlife communities may be retained in the landscape by utilising a variety of these silvicultural systems and varying rotation ages, while still providing a continuous flow of economically viable fibre (Stelfox 1995). Also, it is impossible to meet the habitat needs of all species with any one silvicultural system (Wedeles and Van Damme 1995).

2.4 THE MULTI-COHORT FOREST MANAGEMENT CONCEPT

The concept of Multi Cohort Forest Management (MCFM) began with Bergeron and Gauthier (Bergeron and Harvey 1997; Bergeron *et al.* 1999a; 1999b; 2004; 2007), Harvey (Harvey *et al.* 2002) and Groot's (Groot *et al.* 2004b) work on fire cycle characterisation in the boreal forests of north-western Quebec. The varying fire cycle lengths and intensities in the boreal forests of the region resulted in a natural multi-cohort structure and they reasoned that the multi-cohort features of naturally disturbed forests can be partially emulated by appropriate silvicultural systems. Stands with all or none of the over-story removed by natural disturbances tend to regenerate to a single age class, while those that have had varying amounts of the over-story removed tend to develop into stands with multiple age classes (Long 1998, McCarthy 2001). Artificially creating and preserving these features would prevent the loss of old growth forest structures without a significant reduction in annual harvest levels. Bergeron *et al.* (1999a) proposed a technique employing several silvicultural systems to promote the development and retention of landscape level cohorts: clearcutting followed by planting or seeding in one region; partial cutting in another region; and selection cutting in a third region. These would emulate fire, succession and gap dynamics, respectively (Bergeron *et al.* 1999a).

Boucher *et al.* (2003) developed a cohort classification scheme for the black spruce-moss forest regions of Quebec which divided the forest into multiple cohorts based on the diameter distributions of the stand level trees. Boucher *et al.* (2003) reasoned that the boreal forest is dominated by even-aged stands that have even-sized diameter distributions because the fire cycle in most of the boreal forest is shorter than

the life cycle of most of its constituent species. However, a smaller number of regions have fire cycles that are longer than the life cycles of the component tree species. These regions are influenced by disturbances of lesser intensity (e.g., insect outbreaks and blow-down) and so they contain uneven-aged stands with uneven-sized diameter distributions (Boucher *et al.* 2003). Boucher's group developed a tool based on these stand level diameter distribution differences enabling them to classify stands into multiple cohorts.

Kuttner (2007) incorporated a broader range of stand structural attributes in his analysis of the forests of northeastern Ontario in order to develop a more complete appreciation of the structural and compositional distinctions within and among the cohorts. This approach allowed for the establishment of an objective basis for mixedwood forest cohort classification beyond the rudimentary diameter distributions.

The baseline natural structure derived from these techniques can be used as a reference point from which to develop a silvicultural system able to produce comparable forest compositions and structures. These artificially induced configurations would reflect the differences in forest structure between a "regulated" or "normal" forest and a multi-cohort natural forest. Alternative means proposed to achieve these aims include varying rotation lengths to allow for the accumulation of old growth, and varying silvicultural methods to accommodate and encourage multiple cohorts (Groot *et al.* 2004a, Kuttner 2005) (Figure 1).

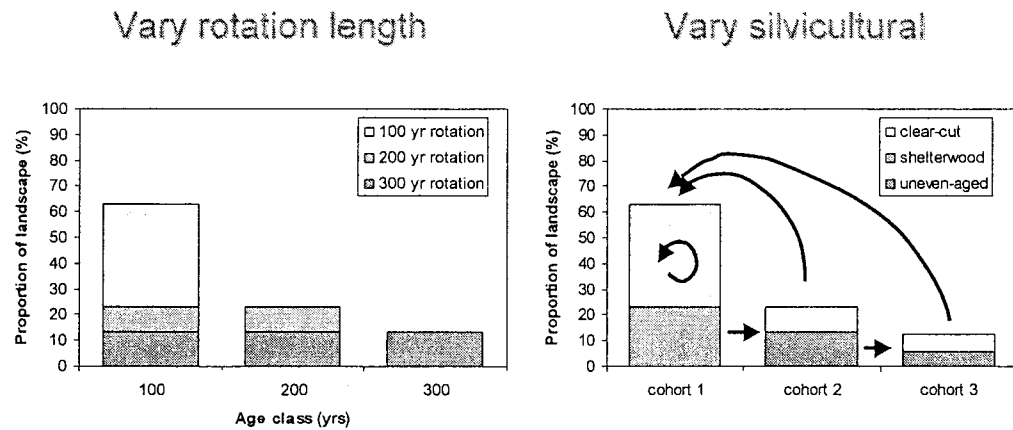


Figure 1. Two approaches to maintain structural diversity.

Source: (Groot *et al.* 2004a)

Current silvicultural practices often lead to a curtailment of stand age-class distributions that results in an over representation of early stage forest cover types and a consequent reduction of older ones (Bergeron and Harvey 1997; Weber and Flannigan 1997), along with more single species stands and fewer mixedwoods. This has led to a declining abundance of the animal species associated with mixedwood forests and with the key habitat attributes of older forest cover types, as these habitat attributes have disappeared from the landscape (Imbeau *et al.* 2001; Drapeau *et al.* 2003). The goal of traditional forest management is to regulate the forest for ease of management and planning.

The fundamental basis for MCFM is the emulation of regional disturbance regimes and their effects on the composition and structure of the forested landscape. An understanding of the frequency, intensity, duration and cause of these disturbance regimes is necessary in order to develop the baseline landscape structure from which the current cohort structure can be derived (Attiwill 1994; Bergeron and Harvey 1997). Silvicultural and management systems can then be developed which attempt to emulate

this baseline structure, in order to allow management for fibre while still allowing essential ecosystem functions to be maintained within the larger, forested landscape (MacDonald 1995). However, residual spatial legacies from previous management regimes may take in excess of 200 years to disappear from the landscape (James *et al.* 2007), demonstrating that MCFM is a long term management strategy.

Harvesting operations may be modified to match the prevailing natural disturbance cycle for the purpose of more closely aligning the effects of forest management with the effects of natural disturbance (Niemela 1999). MCFM promotes an increase in the rotation lengths of selected stands to reflect more accurately the prevailing landscape disturbance intervals. It may also ensure the preservation of vital habitat elements, without the disruption caused by extended rotations and deferred harvests. It withdraws sections of the land-base from the regulated harvest rotation in order to preserve the structural features of old growth stands (Bergeron *et al.* 1999b).

The selection system is the one which best meets the requirements of maintaining the structure of the third cohort class, as it retains a diverse range of stand structures on site (Wedeles and Van Damme 1995). It involves the removal of trees in small groups or singly (Forestry Canada 1992) to create an uneven-aged stand. It can be used to create and maintain stand structure and species diversity for economic, forest productivity, wildlife and genetic conservation reasons (Wedeles *et al.* 1995).

This system of partial cutting can bequeath structural legacies approximating natural compositions (Lee *et al.* 1997) and can help to diminish the impact of tree removal from the stand (Merrill *et al.* 1998; Schieck and Hobson 2000). Retaining these structural legacies is vital to preserving ecological integrity. These partial cuts,

occurring between clearcuts, allow for a series of smaller, limited harvests that lessen the amount of fibre that is lost, while still allowing the stands to age and develop. The number of stands retained in each cohort class is based on the natural disturbance cycle of the region. Therefore, regions with shorter natural disturbance cycles will have shorter harvest rotations and fewer partial cuts between clearcuts (Messier and Kneeshaw 1999).

Figure 2 illustrates a first cohort stand created by allowing the stand to regenerate naturally after clearcutting. This produces a single-age classed stand similar in composition and structure to a natural one. A subsequent partial cutting of this stand produces the two canopy layers and age classes necessary to resemble a naturally occurring second cohort stand. A third selection cut produces the multiple stand structures and essential compositions that create a third cohort stand. A final clearcut would return the stand to the beginning of the first cohort condition.

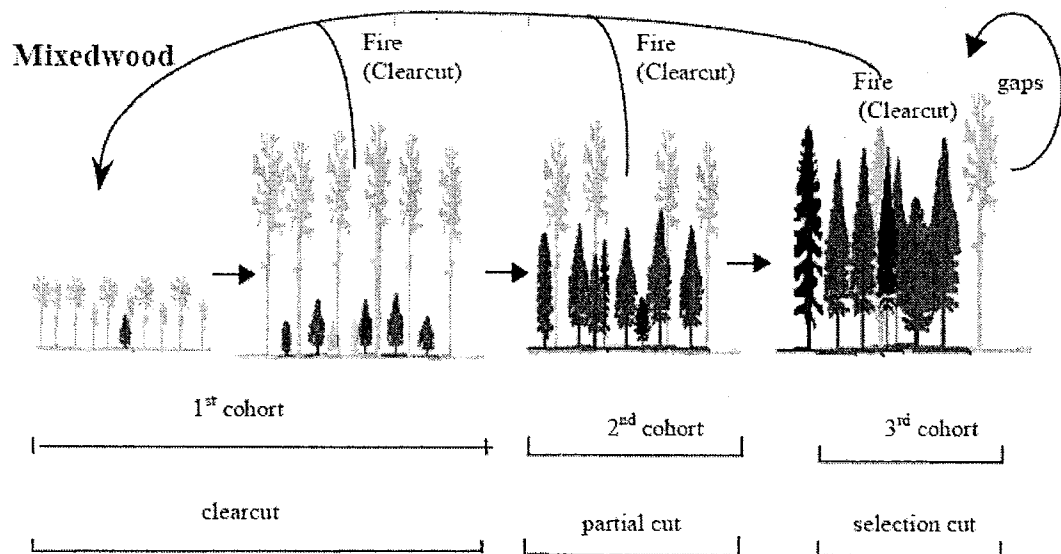


Figure 2. Examples of natural mixedwood dynamics and associated silvicultural treatments.

Source: Adapted from (Bergeron *et al.* 1999a).

This “artificial aging” of the stand allows for the retention of old growth structures on the landscape without the fibre loss of harvest deferrals, or the risk and delay involved in extended rotations.

The challenges involved in employing MCFM include the identification and classification of cohorts; the diversity, location, timing and intensity of the silvicultural systems required to achieve multi-cohort management; the general acceptance and recognition of MCFM as a legitimate strategic and operational approach to forest management; and the difficulty in establishing the baseline for cohorts in nature and emulating it through partial harvesting to maintain cohort biodiversity (Kuttner 2005).

2.5 THE APPLICATION OF WEIBULL FUNCTIONS IN FOREST MODELLING

The Weibull distribution was named after Waloddi Weibull, a Swedish professor, whose influential paper “A Statistical Distribution Function of Wide Applicability” has been extensively used in many fields, including forestry, due to its ability to provide reliable models for a broad range of data sets (Dodson 2006). In forestry research, Weibull modelling has been successfully employed to quantify the diameter distributions of various types of forest stands (Bailey and Dell 1973; Kangas and Maltamo 2000). Results gathered from models built using diameter distributions have been used to characterise forest stands, including classification by age structured cohort (Kuttner 2007). In a two parameter Weibull probability function, the Shape and Scale parameters are derived from regression analysis using diameter distribution frequency data from the stands being analysed. These Shape and Scale parameters are used to interpret the variety of sometimes similar appearing histograms that are produced by Weibull

probability functions. Whereas the Shape parameter affects the shape of the Weibull distribution, the Scale parameter stretches or compresses the distribution (and a third parameter, the Location parameter, affects the location of the curve, but it is not used in a two parameter Weibull distribution.) The Shape parameter (β) describes a progressively more normal distribution as it approaches 3.6 (culminating in a normal distribution at 3.6), indicating the more even-aged stands of Cohort 1. Conversely, a Shape score that is closer to 0 is indicative of the inverse “J” diameter distributions that are found in Cohort 3 stands having a large number of smaller diameter trees combined with fewer, older, larger trees. The Scale parameter (α) with a flatter curve and a longer right-hand tail as it increases describes Cohort 2 or 3 stands which have an increased number of diameter classes present. Unlike the Shape parameter, the Scale parameter is open ended. However, scores ranging from single digits to the low 20s tend to represent Cohort 1 stands, whereas Cohort 2 stands with exceptionally large range of diameter classes can score over 40, with Cohort 3 stands tending to score somewhere in between. The multiple diameter classes found in Cohort 2 stands are useful in distinguishing them from Cohort 1 stands, which can have a similar probability distribution histogram to Cohort 2 stands, but fewer diameter classes (Kuttner 2007).

Using algebraic manipulation, the Weibull probability distribution function can be displayed in a linear form in order to estimate the Shape and Scale parameters through regression analysis. This is accomplished by taking the logarithm of the Weibull function twice and rearranging the equation into a linear form (Dodson 2006). This method of transforming the data allows the Weibull function [1]:

$$F(x) = 1 - e^{-(x/\alpha)^\beta} \quad [1]$$

where,

$F(x)$ = the Weibull function,
 x = DBH (Diameter Breast Height Outside Bark)
 α = the Scale parameter, and
 β = the Shape parameter,

to be expressed as [2]:

$$\ln[\ln\{1/(1-F(x))\}] = \beta \ln(x) - \beta \ln(\alpha) \quad [2]$$

which compares to the more familiar equation of a straight line [3]:

$$Y = mX + b \quad [3]$$

where,

Y equates to $\ln(\ln(1/(1-F(x))))$,
 m equates to β (the Shape parameter),
 X equates to $\ln(x)$ (DBH), and
 b equates to $-\beta \ln(\alpha)$ (the Scale parameter).

An estimate for the probability distribution function is needed in order to complete the linear regression. One accepted method is to use the median of the ranked DBH data (Dorner 1999). The Weibull probability distribution function can then be generated using Microsoft Excel by entering the converted data into the “WEIBULL” function [4] and setting the parameters as:

$$\text{WEIBULL}(\text{DBH}, \text{scale}, \text{shape}, \text{FALSE}) \quad [4]$$

where False generates a probability distribution (as opposed to True, which generates a cumulative distribution). The resulting probability distribution can be plotted against DBH and interpreted to assign Weibull cohort classifications to each stand.

The Weibull probability distribution and diameter class frequency for an example stand with a mid range Shape score (1.88) and a high Scale score (37.72) are shown in Figures 3 and 4, respectively. This stand would be classified in Cohort 2.

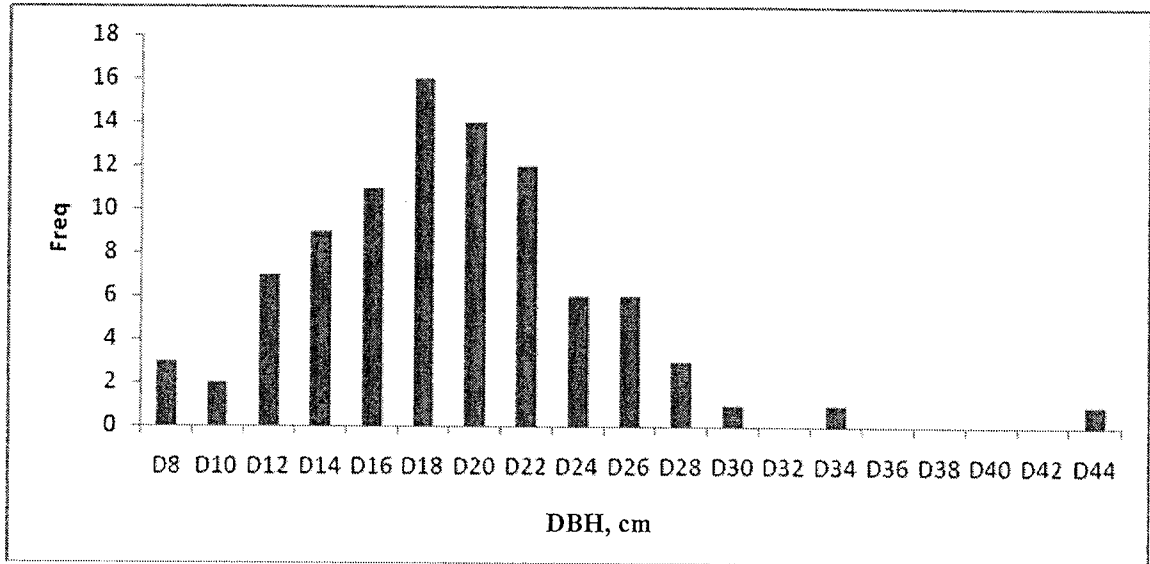


Figure 3. Example diameter class frequency histogram for a Cohort 2 stand.

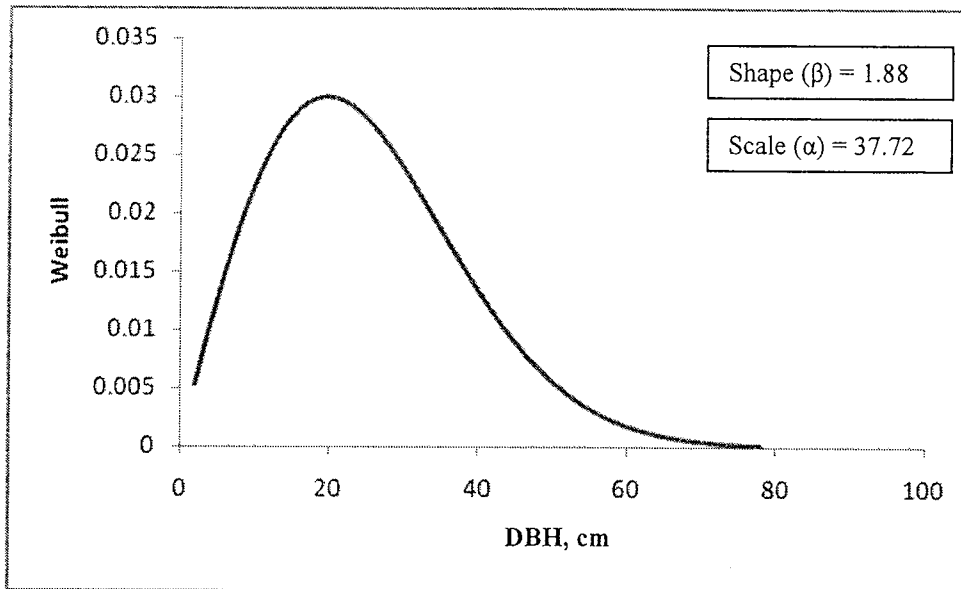


Figure 4. Example Weibull probability for a Cohort 2 stand.

The Weibull probability distribution and diameter class frequency for a stand with a high Shape score (2.33) and a low Scale score (20.81) are shown in Figures 5 and 6, respectively. This stand would be classified in Cohort 1.

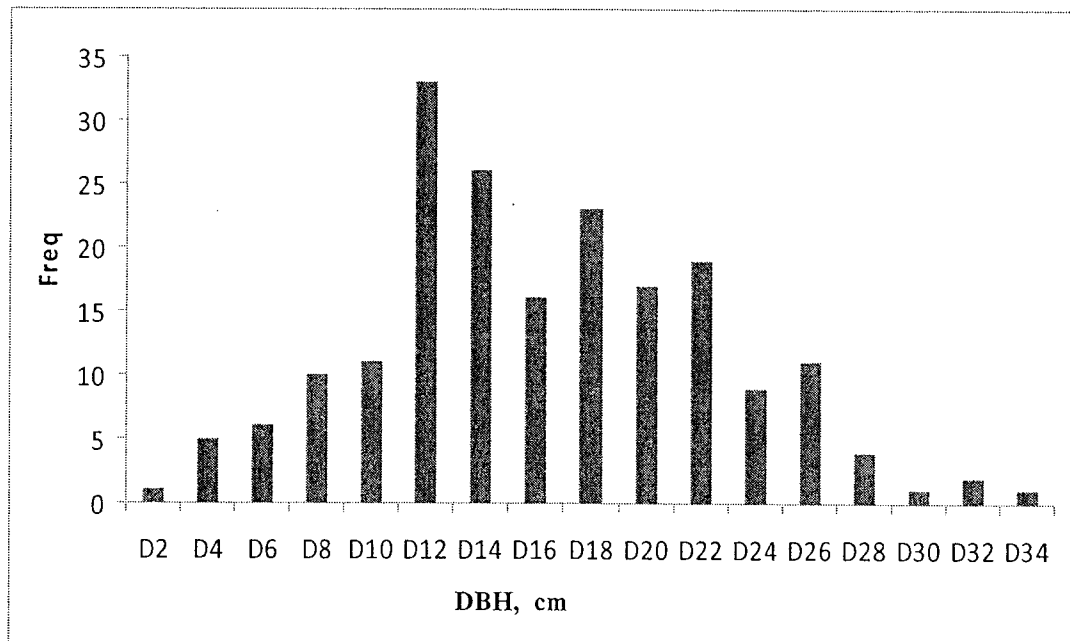


Figure 5. Example diameter class frequency histogram for a Cohort 1 stand

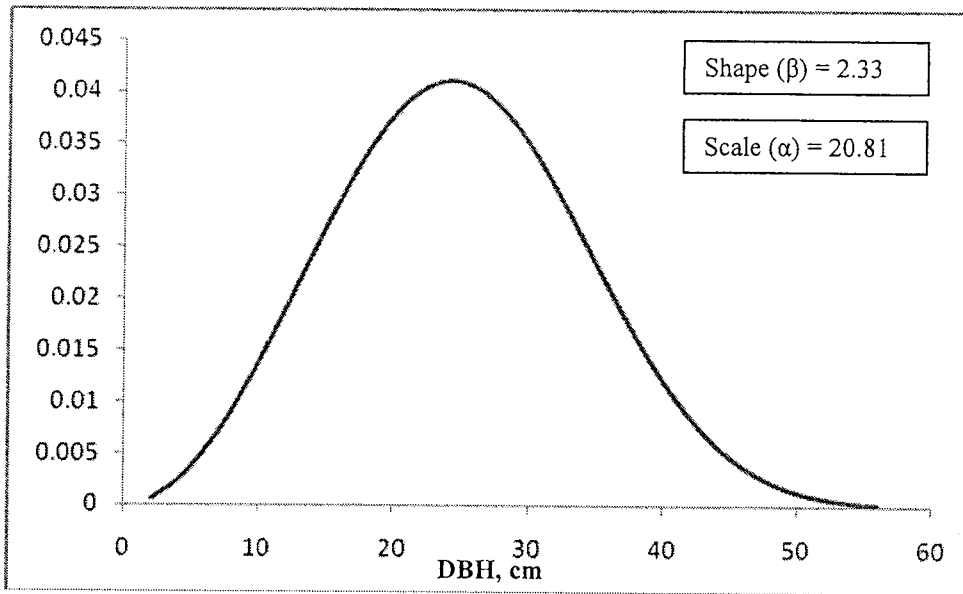


Figure 6: Example Weibull probability for a Cohort 1 stand

The Weibull probability distribution and diameter class frequency for an example stand with a low Shape score (1.34) and a Scale score (32.86) are shown in Figures 7 and 8, respectively. This stand would be classified in Cohort 3.

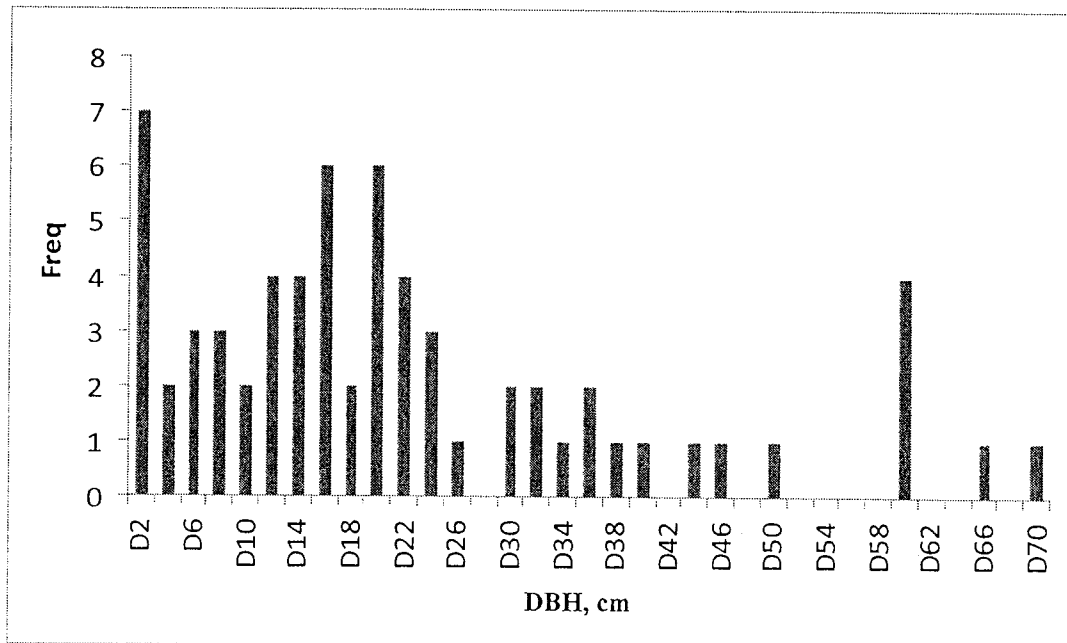


Figure 7. Example diameter class frequency histogram for a Cohort 3 stand.

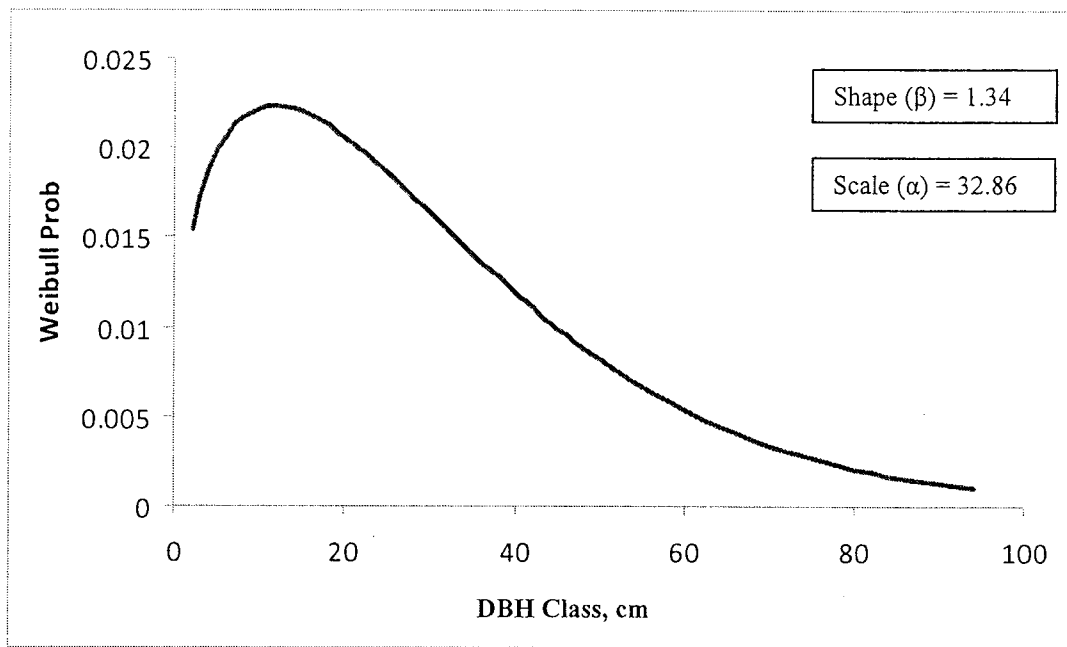


Figure 8. Example Weibull probability for a Cohort 3 stand.

2.6 Discriminant Function Analysis

Application of the Weibull function is demanding (i.e., requires diameter distribution data, a familiarity with various statistical approaches and interpretation of qualitative data), therefore it is appropriate to develop less cumbersome classification methods based on existing and possibly simplified inventory data. To that end, it is reasonable to utilize multivariate statistical techniques to identify useful inventory variables and classification methods (e.g., predictive equations).

In this study, Discriminant Function Analysis (DFA) was chosen for this purpose because it allows us to use an existing classifier value (i.e., Cohort as predicted by Weibull distributions) to assess the success of the classification. The classification is based on 2 or more functions (or equations) which use independent variables, modified

by coefficients, to distinguish the cases (or stands) along the X and Y axes of a spatial plot. Stepwise Discriminant Function Analysis is used to analyse the independent variables of all stands included in the model. The means and standard deviations of each of the independent variables must be in the same range, with approximately normal distributions and no significant deviations or outliers. Group membership is assumed to be mutually exclusive (no stands belong to more than one group) and collectively complete (all stands are members of a group). The steps followed in the Stepwise DFA are described below.

2.6.1 Wilks' Lambda Test

Where DFA identifies more than two groups, Wilks' Lambda, can be used as a test of equality of group means. It is a measure of the total variance in discriminant scores not explained by differences in groups. Large Eigenvalues (representing a large experimental effect) lead to small Wilks' Lambda values: therefore, a small Wilks' Lambda value represents a significant difference in group means caused by the independent variables. If a large proportion of the variance is accounted for by the independent variables then it suggests that there is an effect from the grouping variable and that the groups have different mean values and, therefore, the discriminant model as a whole is significant (Field 2005).

Once the model has been shown to be significant, the next step is to identify which of the individual independent variables differ significantly in means by group. These variables are then retained in the model and used to classify the dependent variables (stands) into groups (cohorts.) To determine whether the observed influence

of each variable was due to chance or to its inherent discriminating power, we compare the values for the F-tests against the maximum value we would expect to get by chance alone, at a significance level of 95%. This test identifies the variables in the model that are correlated but do not suffer from multi-co linearity; a problem that can lead to significant variables being rejected in a Type II error. The stepwise procedure selects the independent variables that maximise the Mahalanobis D-squared distance between the two closest groups.

2.6.2 Box's M Test

Box's M test tests the null hypothesis that the covariance matrices are the same in all of the groups. If the matrices are equal then the assumption of homoscedasticity is met and the statistic will be non-significant. If the statistic proves to be significant, then the observed covariance matrices of the independent variables are not equal across groups and the assumption of homoscedasticity is violated. While Box's M test is extremely sensitive to violations of the assumption of normality, DFA is robust even when the homogeneity of variances assumption is not met, provided the data do not contain important outliers (Garson 2008). Therefore, a failure of Box's M test need not be fatal to the model.

2.6.3 Eigenvalues

DFA creates discriminant Functions which are used to classify the cases of the dependent variable. The Eigenvalues for each Function represent the percentage of the total variance that is explained by each Function. Each of the Functions is represented

on an axis with Function 1, being responsible for a larger portion of the variation found in the model, expressed on the x-axis and Function 2 on the y-axis. The Cohorts separate out along these axes as the model discriminates between them.

2.6.4 Canonical Discriminant Function Coefficients

The Canonical Discriminant Function Coefficients show the relative contribution of each variable to the Functions. They are the correlations between a given independent variable and the scores associated with its discriminant function. They are used to tell how closely a variable is related to each function. The correlations perform as factor loadings representing the set of variables that load most heavily on each dimension, and showing the order of importance of the discriminating variables by unique contribution. The first canonical correlation is always the one that explains most of the relationship. The canonical correlations are the values of b_0 , b_1 and b_2 in the predictive model:

$$Y = b_0 + b_1V_1 + b_2V_2 \quad [5]$$

where,

Y is the discriminant function,
 b_0 , b_1 and b_2 are the discriminant function coefficients, and
 V_1 and V_2 are the variables retained in the model.

However, b_0 is disregarded in our model because it serves to locate the model in geometric space: a property which is not required when we are using the model to discriminate between cohort groups. Our interest lies in the distance between the groups in the model, not the location of the groups in space.

2.6.5 Territorial Map

The Territorial Map is a graphical representation of the areas associated with each cohort, with the centroids displayed in bold. Group centroids are the mean discriminant scores for each of the dependent variables for each of the discriminant Functions. In a 3-group discriminant analysis there are 3 centroids, one for each group. The example plot (Figure 9) shows inter-group distances and group centroids where each group centroid has a numeric symbol and individual cases are not shown (Garson 2008).

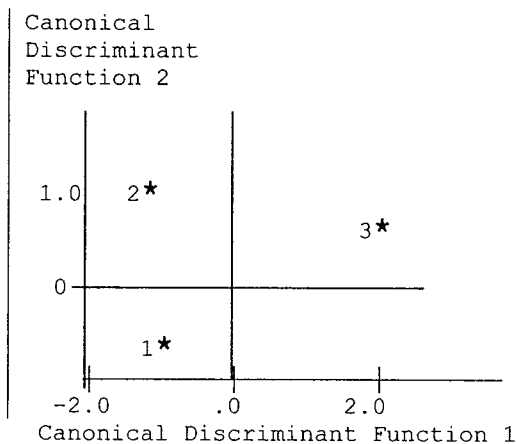


Figure 9. Example Territorial Map of Cohort centroids in discriminant function space.

Ideally, the centroids should be well separated to show the discriminant Functions are clearly discriminating between them. When the centroids are close together or are close to the boundary of another centroid there is an increased chance of misclassification of groups (i.e. a cohort being placed in a group to which it does not belong). The farther apart the centroids are from one another on the territorial map, the better the differentiation between the groups. Thus, the Territorial Map depicts discriminant function space.

2.7 Model validation

It is important to use independent data as a means of validating any predictive model that is created from the DFA. Cross validation allows for a model generated using one data set to be tested using another, independent data set, in order to validate the predictive capacity and accuracy of the model. If the model can predict Cohort status in an independent data set to an acceptable degree of accuracy, then the generalised predictive capabilities of the model can be assumed to be validated.

3. METHODS

3.1 STUDY AREA AND DISTURBANCE HISTORY

3.1.1 Study Area

Boreal forest species comprise the prevailing cover types found within the Dog River-Matawin Forest (Figure 10).

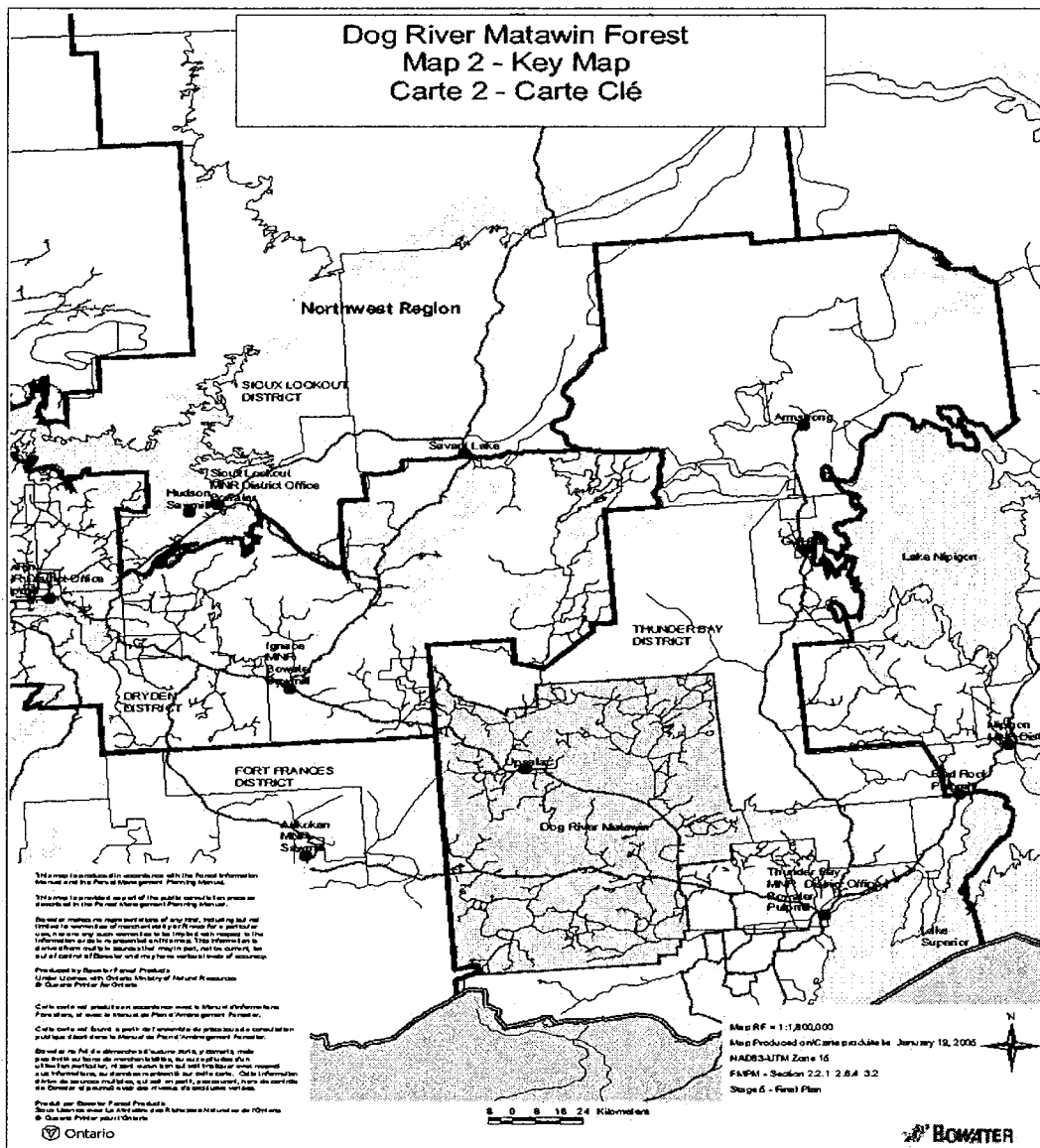


Figure 10. Dog River Matawin Forest in Northwestern Ontario.

Source: DRMF FMP 2005-25.

These cover types or forest units (OMNR 1996) range from homogenous stands of conifer or deciduous species to heterogeneous mixedwoods, with approximately 50% of the DRMF being classified as mixedwood. These mixedwoods are further subdivided into MC1 (14%), MC2 (10%) and MH1 (26%) to reflect the changing proportions of conifer and hardwood within the stands (Van Damme 2005). MC1 is defined as conifer component greater than 50% and trembling aspen less than 20% and trembling aspen + paper birch less than 30%. MC2 is defined as conifer greater than 60% or conifer greater than 50% with a conifer species as the working group. MH1 is the final category on the decision process (Figure 11) and it consists of the mixed hardwood dominated stands that do not fall into the other categories. No further subdivision has been assigned to these stands so that, essentially, 50% of the forest stands have been grouped into one of three broad varieties of mixedwood.

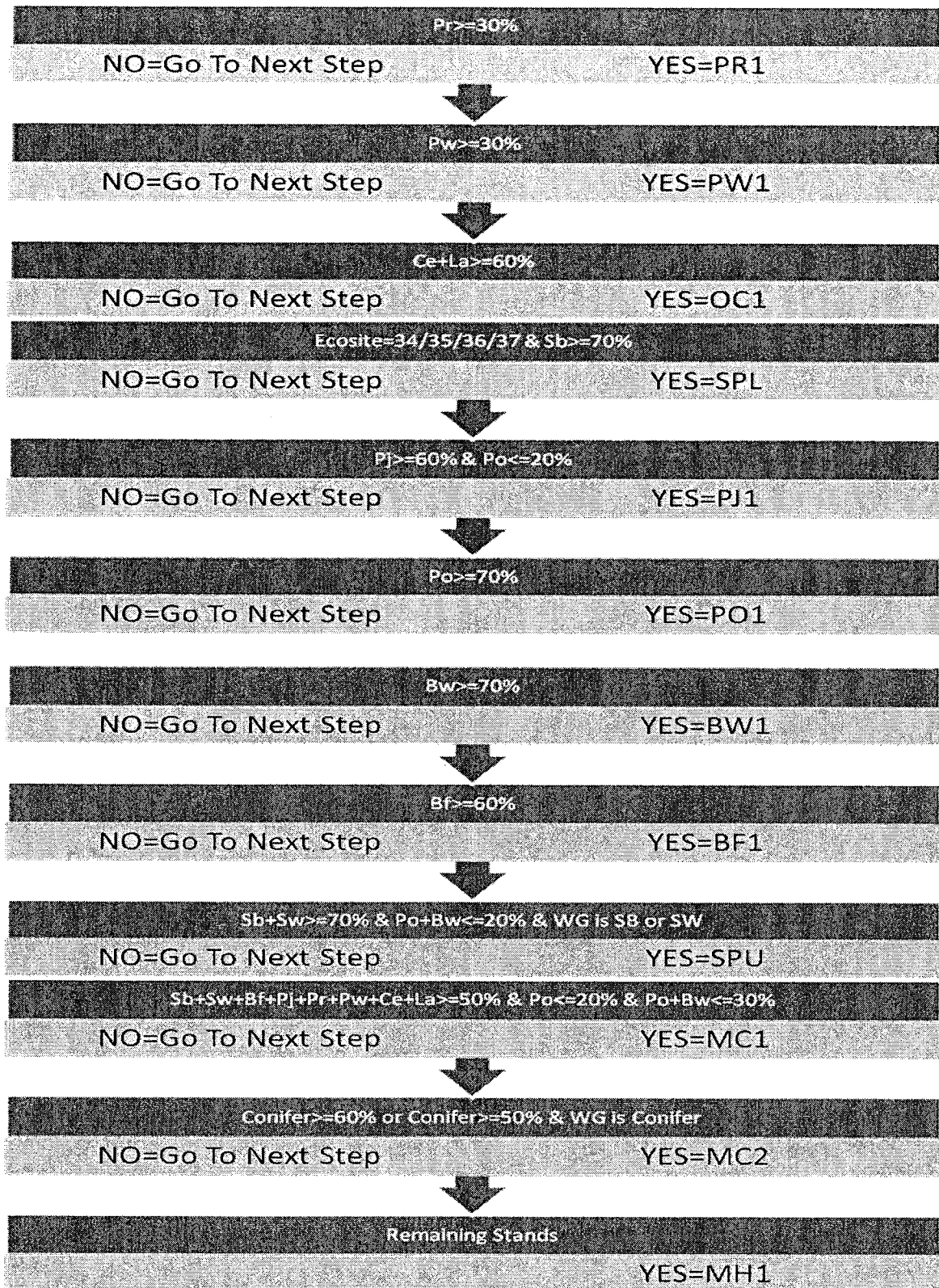


Figure 11. Decision process for stand classification

Source: DRMF FMP 2005-25

3.1.2 Mixedwood Management and Disturbance History

Commercial logging in the DRMF is recorded as early as the 1890s with the issuing of the first Crown Timber Licence. Evidence of logging roads and abandoned railway lines from the early part of the twentieth century indicates that there were substantial harvesting operations present in the forest at that time. The landscape of the forest bears remnants of the old white pine (*Pinus strobus* L.) stands which have been largely converted to trembling aspen by the harvesting practices of this era (Van Damme 2005). Major road building commenced after 1960 with an increase in logging activity as more species were harvested for the mills (e.g., jack pine (*Pinus banksiana* Lamb.) and trembling aspen).

Sizeable fires were recorded for the DRMF in the early 1900s (a large fire in 1936 was attributed to presence of railway lines within the DRMF) but more advanced fire suppression techniques have prevented major occurrences over the past 60 years. However, a significant fire occurred in 1995 (2,220 ha burned) and another in 1996 (2,130 ha burned) which together contributed the majority of the 6,636 ha lost to wildfire between 1995 and 2000 (Van Damme 2005).

The entire DRMF was severely infested with spruce budworm (*Choristoneura fumiferana*) in the late 1960s and early 1970s that resulted in heavy mortality and significant losses of the balsam fir and white spruce components of the mixedwood stands. Chemical insecticide spraying had some success in controlling the spruce budworm population, however the infestation recurred in the late 1990s and the area was aerielly sprayed with the biological insecticide *Bacillus thuringiensis*. Another important insect pest of the DRMF is the eastern tent caterpillar (*Malacosoma*

americanu) which caused major infestations in 1990-92 and 2000-03. Insect outbreaks have been moderate otherwise with only 95 ha of the DRMF being depleted by insects between 1995 and 2000 (Van Damme 2005).

Major wind-throw and blow-down events have occurred at irregular intervals in the DRMF, with mature and old growth conifer stands being the most susceptible to damage. A severe windstorm occurred in 1999 that damaged 5,588 ha of the DRMF and tens of thousands of hectares of adjacent forest. Bowater salvaged 4,952 ha that was severely damaged in that storm and maintained snag trees and standing live trees where possible. Between 1995 and 2000, a total of 5,764 ha was reported lost due to wind and ice storm damage with the 1999 windstorm responsible for most of it (Van Damme 2005). The combined effect of these disturbances has led to the development of stand structures that are consistent with Bergeron's Cohorts 1, 2 and 3. However, the FRI maps do not identify these structural classes, thereby limiting the range of management options.

As part of the of the Dog River-Matawin Forest (DRMF) Forest Management Plan (FMP) 2005-2025, it was proposed to “*evaluate the utility of Yves Bergeron's three cohort system... (which advocates) the use of alternatives to clearcutting to maintain old growth structure in mature forest cover types. One outcome could be a shift from oldest first to an emphasis on harvesting accessible younger stands on shortened rotations in intensive zones*” (Van Damme 2005). Also included in the DRMF FMP is the aim “*To develop stand structures and age class distributions that are consistent with natural patterns*” (Van Damme 2005). The MCFM concept integrates stand structure, composition and age into three general developmental stages (cohorts) based on the time

since the last stand altering disturbance (Bergeron *et al.* 2002; Harvey *et al.* 2002; Kuttner 2007). Through the application of appropriate harvesting and silvicultural techniques, forest landscapes can be made to resemble more closely the natural forest mosaic. The MCFM concept may allow for the existing three classes of mixedwood found in the DRMF (MC1- Mixed Conifer 1, MC2- Mixed Conifer 2 and MH1- Mixed Hardwood 1) to be further sub-classified into their structural cohorts to produce MC1 Cohort 1, 2 and 3 stands, reflecting both composition and structure.

3.2 DATA

3.2.1 Model Development

3.2.1.1 Ontario MNR Forest Resource Inventory (FRI).

The standard Ontario Ministry of Natural Resources (OMNR) FRI was designed in 1946. It uses aerial photography to identify and delineate forest stands that have similar characteristics: species, age, stocking, site class and height. The aerial photography used for this FRI consists of the standard black and white 9 x 9 inch photographs at a scale of 1:20,000. This scale matches the digital Orthorectified Base Maps (OBM) produced by the OMNR. Some field data is collected at this time but it is mainly used to assist the photo interpreters in tree species identification, as well as tree age and height validation. It is not collected in a way that would be useful for any statistically valid inference about the nature of the forest, but consists of a series of easily accessible plots which can be used for calibration of the interpreted aerial photographs. Forest stands are then delineated by the interpreters and the stand attributes are recorded (stand species composition, age, height, stocking and site class) as are other landscape features

(e.g., lakes and non-productive forest land) and man made features (e.g., roads, hydro lines). These stand attributes are recorded electronically and are used in the production of FRI maps. Yield tables (e.g., Plonski's, local volume tables) are then used to estimate the volume of wood in the stands by species on the basis of estimated basal area.

3.2.1.2 Abitibi-Bowater Continuous Forest Inventory (CFI)

In 1996, Bowater Inc. (now Abitibi-Bowater) resolved to design and produce an enhanced forest resource inventory that would complement the standard Ontario FRI. This new inventory would provide stock and stand tables, yield curves, accurate map layers for use in GIS applications, ecosystem classifications, succession pathways, stand structures and habitat supply models. The CFI would lead to more accurate yield predictions, increasing certainty of wood supply and management decisions that could be more easily defended. In addition, biodiversity, conservation and natural pattern emulation objectives would be better formulated and evaluated over time. Future wood supply shortages would be identified and ameliorated, and the continuous nature of the growth and yield sampling would allow the inventory to evolve (West 2006).

The sample points were located in clusters at the corners of 2 km x 2 km squares (Figure 12.) The sample points were designed to be 200 m x 200 m squares with three plots clustered 20 m apart at each of the corners, for a total of 12 plots per sample point. A completely random sample design is often impractical and prohibitively expensive in forest data collection due to the size of the land base and the costs involved in transporting sampling crews to the many remote locations. A systematic random sample design was chosen for the CFI to allow for a compromise between sampling feasibility

and valid statistical analysis. A grid was produced and overlain on the Bowater management units using a random starting point from outside the sample area. The 1976 FRI was used to determine the expected range of variation within the land base and the number of points required was calculated within a 95% confidence interval. The resulting sample intensity was 2-3 times greater than for a conventional FRI.

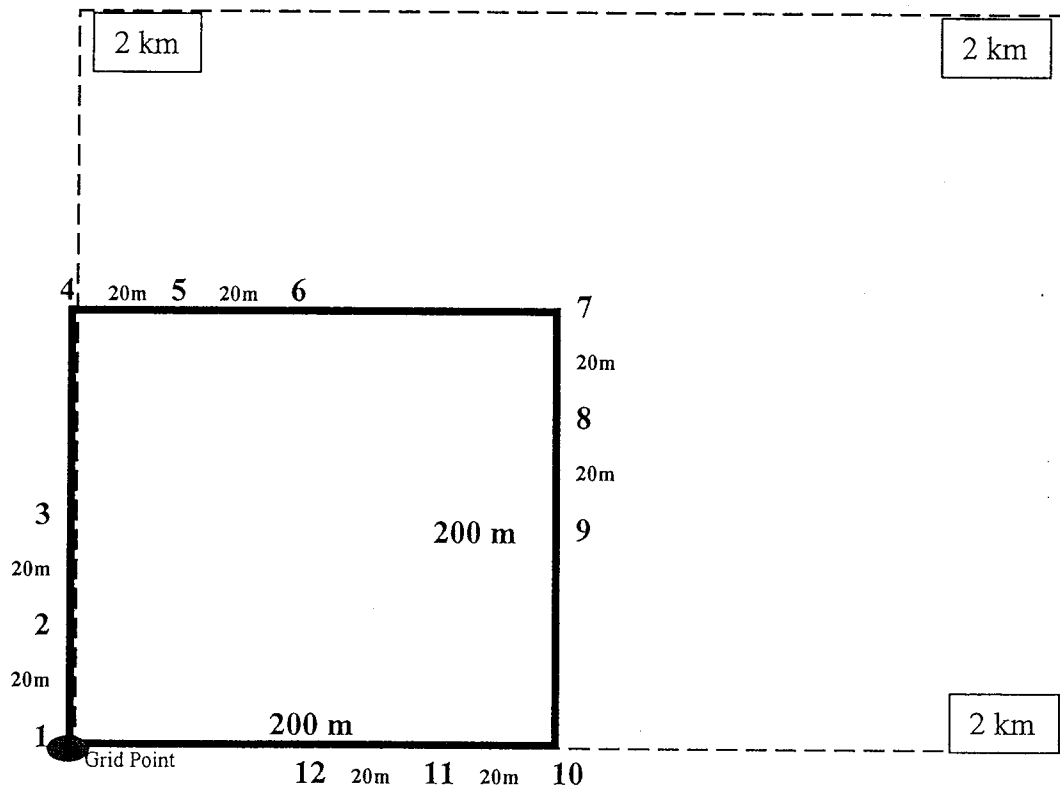


Figure 12. CFI Sample Plot Design (not to scale).

Source: (West 2006)

The following stand characteristics were collected at each of the plot locations, according to the standards of field data collection for FRI used by the OMNR, with additional specifications for procedures not covered by the OMNR guidelines (West 2006):

- **Basal area and diameter at breast height outside bark (DBH) distribution:** using a BAF 2 wedge prism to record tree species and basal area, and callipers to measure DBH at 1.3m in 2 cm diameter classes for all “in” trees,
- **Snags:** a tally of all dead standing stems (greater than 10 cm DBH and 3 m height) into 2 cm diameter classes using callipers,
- **Height:** to the nearest 0.5 m of a dominant or co-dominant working group tree, using a Suunto with the distance measured from tree using a 30m tape,
- **Diameter (DBH):** of the same tree used above,
- **Age:** of the same tree used above, taken at one borer handle length up from the ground,
- **Regeneration:** understory tree species (up to 2 m) into percentage cover classes,
- **Forest Ecosystem Classification (FEC):** at the corner plots only, including an ecosite classification, soil classification and a description of the vegetation type.

Black and white aerial photographs at a scale of 1:20,000 were provided by the OMNR for interpretation by qualified personnel. All field data were entered into a GIS database and incorporated into map layers.

A trend analysis was conducted to compare the data from the original FRI to the new data contained in the CFI (Van Damme 2005). This analysis revealed that the CFI data corresponded with the yield curves, growing stock estimates and dominant species generated by the original FRI. However, the CFI data showed that more than half of the sampled area was multi-layered with more extensive age class distributions than was originally conceived. This was in direct contrast to the FRI assumption of even-aged

forest condition and indicated that the structure of these stands was more complex than would be found in even-aged stands. It was decided in the 2005-2025 FMP that an evaluation of the multi-cohort classification system would be appropriate for this area in order to determine the baseline cohort status.

All of the raw data used in this study can be found in the Appendices.

3.2.2 Model Validation

3.2.2.1 Ontario MNR Permanent Sample Plots (PSP)

Permanent Sample Plots are used by the MNR as an accurate and efficient method of determining growth and yield in a stand through repeated measurements. The MNR conducts long-term monitoring of an established network of PSPs in managed and natural forests across the province. PSPs serve a vital role in forest monitoring and modeling, as stand growth and dynamics can be estimated directly from the repeated measurements of various ecosystem elements. The main objectives in establishing PSPs are to: provide yield curves for use in strategic wood supply analysis; assess forest stand dynamics, succession, regeneration, in-growth and mortality; maintain a comprehensive database of stand growth and yield; create models, methods and management tools for the evaluation and calibration of growth and yield models; and derive and define stand and tree attributes for inventory purposes (OMNR 2008). Two types of plots have been utilized throughout Ontario. The first is a complete PSP (described below) and installed by OMNR personnel. The second is the Permanent Growth Plot (or PGP), a scaled down version of the PSP, installed by agencies under contract to the OMNR. The plots

used for model validation were all PSP and the datasets were provided through the OMNR.

The measured size of a full PSP is 6400 m². Nested within this larger plot are several sub-plots: Growth plots, Stocking plots, Mortality plots, Vegetation plots and Down Woody Debris lines. The three Growth plots and 27 Stocking plots contained within the larger PSP provide the data required for the validation of any model produced from either the FRI data or the CFI data. The Growth plots each have a radius of 11.28 m for an area of 400 m² each, and providing a three sub-plot total of 1200 m². Tree heights are measured using a clinometer, dbh is measured using a diameter pole with trees being grouped into 2 cm diameter classes, and age is measured using an increment borer. The 27 smaller Stocking plots are located along radial lines 120° apart around the PSP. They each have a radius of 1.13 m and an area of 4 m², for a total of 108 m². PSPs have a 120 m buffer surrounding them for protection and for plot integrity.

3.3 SELECTION OF STUDY PLOTS FROM FRI AND CFI

The GIS database was filtered to select the layers from the CFI that corresponded to the mixedwood sites of interest: MC1, MC2 and MH1. Another filter was then applied to select only stands in the CFI which had a corresponding FRI data set (Figure 13). This was necessary because, after the study was begun, it was found that the CFI data set was not always complete for each sample point and that, towards the end of the inventory, some of the stands were not sampled.

The selected CFI stands were then examined to determine if they met the requirements needed to be included in the analysis. The mixedwood layers were colour

coded for ease of identification and each stand was verified to confirm that the stand composition was consistent with the recorded stand classification.

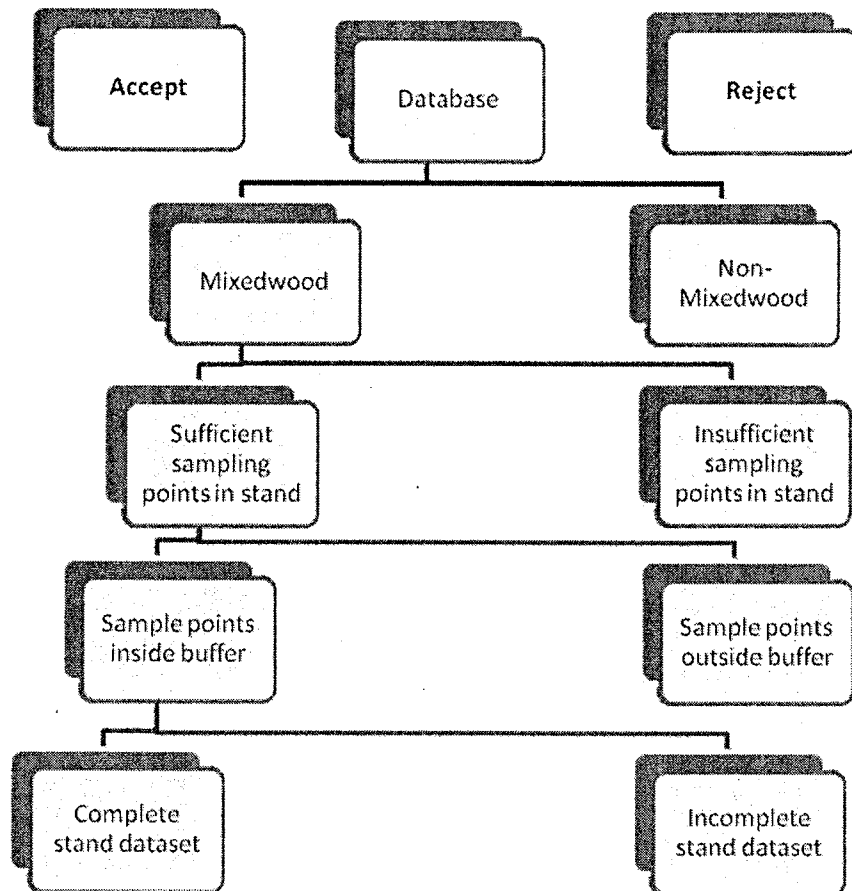


Figure 13. Flow chart for CFI stand classification.

The first requirement was that the stands had to have at least three sample points in order to provide sufficient and accurate data for analysis. Figure 14 shows an MC1 stand that has insufficient sample points to allow for analysis. One of the sample points (stars) lies in an adjacent non-MC1 stand (bottom right point), and two of the sample

points lie within an adjacent MC1 stand (top right and bottom left points). This stand was rejected.

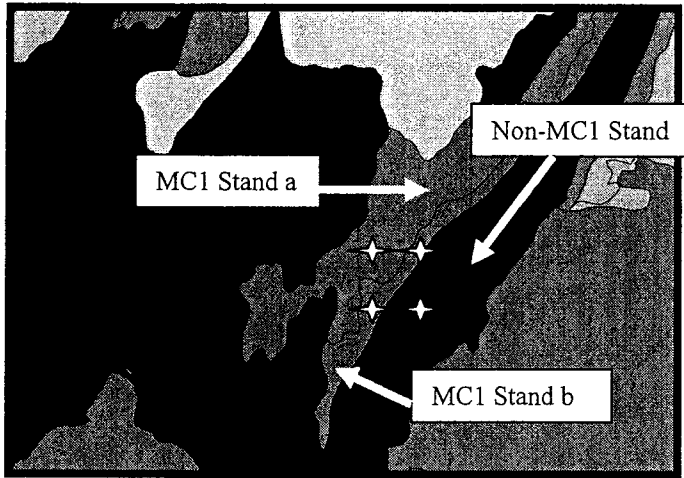


Figure 14. Rejected MC1 stand.

The next requirement was that the sample points must not lie within a 5-metre buffer zone around the stand perimeter. This buffer zone was added as an attempt to correct any errors in the geographic location of the recorded sample point. It was reasoned that sample points that fell wholly within the buffered stand were more likely to be an accurate sample from the selected stand.

Figure 15 shows a rejected MC2 stand. Though enough sample points were contained within the stand (3), one of the points fell within the 5-metre buffer zone, leaving only two points wholly contained within the stand boundary.

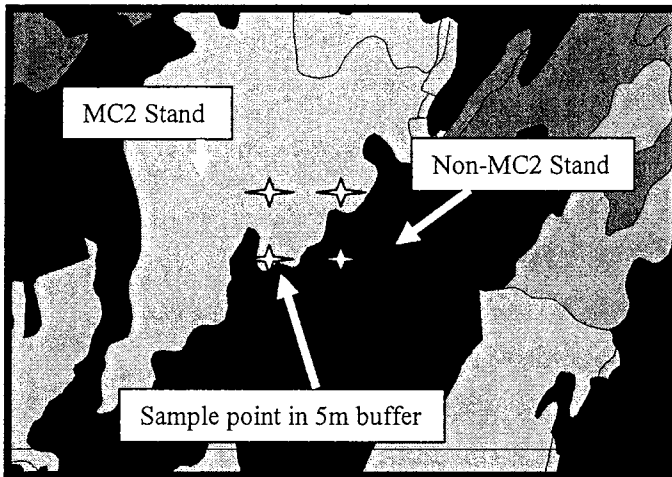


Figure 15. Rejected MC2 stand.

Stands that had been verified for composition and adequate sample points contained within the buffered perimeter were then selected for analysis. Figures 16 and 17 show acceptable stands which for study inclusion. The final selection criterion was that each of the selected stands must have corresponding and complete diameter distributions in the CFI to produce Weibull functions. The data from each of the sample points were then pooled to give a representative data set for each stand in the analysis.

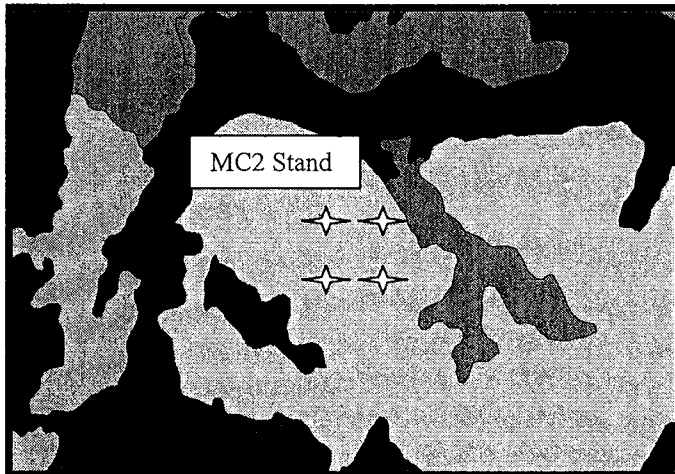


Figure 16. Accepted MC2 stand with 4 sample points.

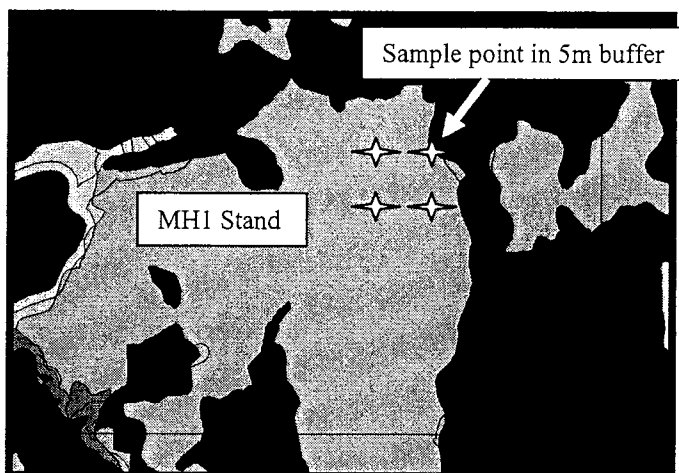


Figure 17. Accepted MH1 stand with 3 sample points.

3.4 SELECTION OF VERIFICATION PLOTS FROM PSP

The PSP plots were selected aspatially and were used as an independent data set to verify the accuracy of any successful FRI or CFI models. The PSP plots fell within the boundaries of the DRMF and, further, they met the requirements of mixedwood stands as defined in this study. The stands in the PSP were compiled in a Microsoft Access database and were filtered according to species composition with the mixedwood stands being retained for use in the analysis. The selected stands were examined to confirm that they had the complete and representative datasets required to derive the stand variables used to verify any successful model created using the FRI or CFI datasets. The selected stands were further divided into one of the three mixedwood stand designations: MC1, MC2 or MH1 based on the species compositions found in the DRMF FMP (Van Damme 2005).

3.5 DERIVATION OF PREDICTIVE MODEL FOR STAND STRUCTURAL CLASSIFICATION

Table 1 illustrates the process that was followed through the different steps to derive a predictive model for Cohort classification.

Table 1. Flow chart of methods for Cohort classification.

Step	1	2	3	4	5
Approach	Weibull	FRI	Alternate Classifiers	Validation	Application
Data	Diameter class Information (CFI)	FRI data plus cohort label from CFI (1)	CFI dataset (existing & new variables) plus cohort label from (1)	Classifier variables from PSP plus Weibull cohort label	
Action	Apply Weibull Function analysis	Apply DFA	Apply DFA – identify classifier variables	Apply classifier equations	
Outcome	Assign cohort ID	Same cohort groupings -> success!-> end Different cohort groupings -> unsuccessful -> move to (3)	Same cohort groups -> success! -> classifier equations created	Same cohort groupings -> success! End Different cohort groupings -> unsuccessful -> Weibull analysis still the best alternative	MC1, MC2, MH1 classifications

At the completion of steps 2, 3 and 4 there is a decision step based on the success of that particular step. The following paragraphs provide additional detail.

Cohorts were assigned to the 68 selected stands using diameter data from the Bowater CFI dataset and the Weibull analysis as described in Section 2.6 and 2.7. For model validation, cohorts were also derived for the 24 mixedwood stands selected from the PSP data.

As a first test of the ability of DFA to distinguish different groups based on the stand attributes found in the FRI, the 68 stands were run through the analysis.

The CFI data presented the opportunity to use directly measured stand characteristics (e.g., age, height, site class and stocking) and to create derived stand attributes such as species richness, evenness and coefficient of variation. The list of derived variables for the DFA based on CFI information is summarized in Table 2. In total, 9 attributes were included in the analysis. These Cohort classifications derived from CFI data were compared to the Weibull classifications to provide a gauge of model accuracy.

Following completion of the DFA (using SPSS 16.0) the results allow for: a) the identification of a subset of variables that distinguishes the cases, and b) the creation of equations (or functions) that describe the relative position of each case in 2-dimensional space. In order to test the success of this approach, the number of cases assigned to each cohort were compared to those assigned based on the Weibull analysis. Using the two functions produced by the DFA, and the appropriate variables, the location of each PSP stand in 2-dimensional space was determined. Once again, the success of this approach was determined by comparing the number of cases assigned to each cohort using the equations resulting from DFA and the Weibull analysis.

3.6 DERIVATION OF VARIABLES USED IN PREDICTIVE

MODEL

The Weibull functions were used to give the initial cohort classification for each of the mixedwood stands in the CFI. Subsequent cohort classifications were derived by using a suite of indices to distinguish between the three stand cohort types. These

indices were then examined using Discriminant Function Analysis (DFA), which works most effectively when given a series of variables to differentiate amongst, to generate classification diagrams and algorithms. Table 2 summarizes the variables used in the analysis. The remaining variables used in the analysis (age, height, site class and stocking) were taken from direct measurements.

Table 2. Definition of variable abbreviations.

Variable	Abbreviation	Explanation (incl. equation)	Reference
Shannon's Diversity Index	H'	usually employed to describe levels of species diversity found within a stand. A useful tool for measuring the diversity of tree diameters in a stand: $H' = - \sum P_{cl} \cdot \log (P_{cl}) \quad [6]$ where P_{cl} is the proportion of stem diameters that falls within each of the 2 cm classes.	Boucher et al. 2003; Kuttner 2007
Diameter Class Evenness	Even	compares the observed diversity of Dbh classes to the maximum possible diversity of Dbh classes. It was calculated using Pielou's formula $Even = H' / \log S \quad [7]$ where H' is Shannon's diversity index and S is the Diameter class richness	Kuttner 2007
Diameter Class Richness	DCRich/DCR	a simple count of the number of different diameter classes contained within a sampled stand. For example, a stand in which all of the trees are found in six of the diameter classes was found to have a Diameter Class Richness of 6.	Kuttner 2007
Co-efficient of Skewness	(CofS)	measures the unevenness of the observed diameter class distributions. A stand with all tree diameters distributed normally would have a skewness of 0; A stand that had a high proportion of large diameter trees would have a positive skewness. $CofS = \Sigma \{ (x_i - \bar{x})^3 / (n-1) \} / s_x^3 \quad [8]$ where x_i is the diameter class of the sampled tree, \bar{x} is the mean diameter class, n is the total number of trees found within the stand, and s_x is the standard deviation.	Boucher et al. 2003; Kuttner 2007
Co-efficient of Variation	(CofV)	A measure of variation of diameter classes $CofV = s_x \cdot (100 - \bar{x}) \quad [9]$ where, s_x is the standard deviation and \bar{x} is mean diameter class.	Boucher et al. 2003;

4. RESULTS

4.1 CLASSIFICATION INTO COHORTS

Application of Weibull analysis showed that the three types of cohort (1, 2 or 3) were spread across the three types of mixedwood stands (MC1, MC2 or MH1) (Table 3). It appears that the majority of MC1 stands were classified as either cohort 1 or 2 (23 out of 29) and the majority of MC2 stands were classified as cohort 3 (10 of 16). The largest number of MH1 stands were classified as cohort 2 (11 out of 23).

Table 3. Stand classification using CFI Mixedwood types and Weibull analysis.

CFI STAND TYPE	NUMBER OF STANDS IN EACH WEIBULL COHORT			TOTAL
	1	2	3	
<u>MC1</u>	11	12	6	29
<u>MC2</u>	3	3	10	16
<u>MH1</u>	5	11	7	23
<u>Total</u>	19	26	23	68

4.2 CLASSIFICATION OF STANDS USING FRI DATA

Means and standard deviations of each of the independent variables were all in the same range, with approximately normal distributions and no significant deviations or outliers. Group membership was mutually exclusive (that is, no case belonged to more than one group) because each of the stands was grouped according to its mixedwood designation

(i.e., MC1, MC2 or MH1). The stands were collectively complete (that is, all stands were members of a group). Table 4 shows the Tests of Equality of Group Means.

Table 4a and 4b. Test of equality of Cohort group means (full FRI.)

	Wilks' Lambda	F	df1	df2	Sig.
a. 3 cohorts (Cohorts 1, 2 & 3)					
Stand Type	.972	.940	2	65	.396 ^{ns}
Ht	.962	1.289	2	65	.283 ^{ns}
Stock	.995	.170	2	65	.844 ^{ns}
Age	.952	1.652	2	65	.200 ^{ns}
Site Class	.942	2.001	2	65	.143 ^{ns}
b. 2 cohorts (Cohorts 1 & 2/3 combined)					
Stand Type	.973	1.798	1	66	.184 ^{ns}
Ht	.976	1.637	1	66	.205 ^{ns}
Stock	.995	.339	1	66	.562 ^{ns}
Age	.998	.113	1	66	.738 ^{ns}
Site Class	.960	2.723	1	66	.104 ^{ns}

^{ns} = not significant at 95% level.

There was no significant difference among the cohort group means of the FRI data set (at $p \leq 0.05$), therefore none of them were retained in the model. Furthermore, Wilks' Lambda values were all very high, indicating that none of them played a significant role in discriminating between mixedwood cohorts using the FRI data set.

A subsequent attempt to use the simple FRI data set to identify only two groups (by combining cohorts 2 and 3) was also not successful (Table 4b).

4.3 CLASSIFICATION OF STANDS USING CFI DATA

The test of equality of cohort group means using the CFI data set (Table 5) identified significant differences (at $p \leq 0.05$) in group means based on five variables - Shannon's Diversity Index (H'), Evenness (Even), Diameter Class Richness (DCR), Coefficient of Variation (C of V) and Coefficient of Skewness (C of Sk).

Table 5. Test of equality of Cohort group means for CFI

	Wilks' Lambda	F	df1	df2	Sig.
Stand Type	.972	.940	2	65	.396
Ht	.962	1.289	2	65	.283
Stock	.995	.170	2	65	.844
Age	.952	1.652	2	65	.200
Site Class	.942	2.001	2	65	.143
H	.607	21.060	2	65	.000***
Even	.823	6.969	2	65	.002**
D C Rich	.602	21.458	2	65	.000***
C of V	.684	15.014	2	65	.000***
C of Sk	.777	.931	2	65	.000***

^{ns} = not significant at 95% level, ***=significant at 99.9% level

To determine whether this influence was due to chance or to the inherent discriminating power of each of the variables, the analysis software (SPSS 16.0) compared the values for the F-tests against the maximum value we would expect to get by chance alone, at a significance level of 95%. Three variables were retained through this procedure: DCR, C of V and Even (Table 6).

Table 6. Significant variables retained in the predictive model for CFI Cohort status.

Step	Entered	Wilks' Lambda						
		Statistic	df1	df2	Exact F			
					Statistic	df1	df2	Sig.
1	DCR	.602	1	2	21.458	2	65	.000***
2	CofV	.424	2	2	17.136	4	128	.000***
3	Even	.334	3	2	15.349	6	126	.000***

^{ns} = not significant at 95% level, ***=significant at 99.9% level

Box's M test was significant indicating that the assumption of homoscedasticity was violated. However, the data for this test do not contain outliers.

Table 7 shows the Eigenvalues for each variate and the percentage of the variance of each Function that is explained by that variate. A larger Eigenvalue reflects greater separation between the groups. In this case, Function 1 explains 55.8% of the variance between groups while Function 2 explains 44.2%. This illustrates that the differences between groups can be explained in terms of two underlying dimensions. Each of the Functions represents an axis along which the Discriminant Function Analysis separates the Cohorts. In this case Function 1, being responsible for a larger portion of the variation found in the model, is expressed as the x-axis and Function 2 as the y-axis. The Cohorts separate out along these axes.

Table 7. Eigenvalues of Functions 1 and 2 in Predictive model.

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	.818	55.8	55.8	.671
2	.648	44.2	100.0	.627

Function 1 was strongly positively influenced by Coefficient of Variation (0.911) and strongly negatively influenced by Evenness (-0.717). Function 2 was strongly positively influenced by Diameter Class Richness (1.006) indicating that group separation in both Functions 1 and 2 is determined by the difference between the dependent variables (Table 8). The first canonical correlation is always the one that explains most of the relationship.

Table 8. Canonical discriminant function coefficients.

	Function	
	1	2
Even	-.717	.183
DCR	.158	1.006
CoV	.911	-.278

Therefore, the predictive model (equations 10 and 11) which allows us to separate the cohorts is:

$$\text{Function 1: } X = 0.158DCR_{rich} + 0.911CofV - 0.717Even \quad [10]$$

$$\text{Function 2: } Y = 1.006DCR_{rich} - 0.278CofV + 0.183Even \quad [11]$$

The Territorial Map (Figure 18) is a graphical representation of the areas associated with each cohort, with the centroids displayed in bold.

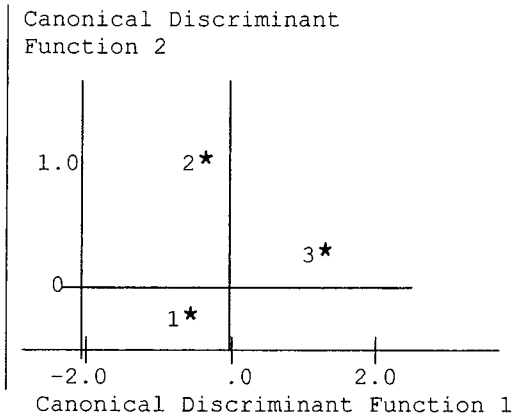


Figure 18. Territorial map of Cohort centroids in discriminant function space.

This is a 3-group discriminant function analysis and so there are 3 centroids, one for each cohort. The three centroids are located well inside their inference spaces and away from the boundaries.

Table 9 shows how well the discriminant functions work and if they work equally well for each group. The Original classification classifies each sample using the Weibull cohort status; the Predicted group membership is the classification derived from the discriminant function analysis.

Table 9. Comparison of classification using Weibull Analysis and DFA based on Continuous Forest Inventory datasets.

		DFA Predicted Group Membership			
		1	2	3	Total
Count	1	14	3	2	19
	2	3	20	3	26
	3	0	6	17	23
%	1	73.7	15.8	10.5	100.0
	2	11.5	76.9	11.5	100.0
	3	0.0	26.1	73.9	100.0

Bolded numbers indicate correct classification by DFA

The model correctly classified 75.0% of the overall cases (73.7% of cohort 1, 76.9% of cohort 2 and 73.9% of cohort 3). The model correctly classified 14 of the 19 Cohort 1 stands as Cohort 1, but incorrectly classified 3 of the 19 Cohort 1 stands as Cohort 2, and 2 of the 19 Cohort 1 stands as Cohort 3. The model correctly classified 20 of the 26 Cohort 2 stands as Cohort 2, but incorrectly classified 3 of the 26 Cohort 2 stands as Cohort 1, and 3 of the 26 Cohort 2 stands as Cohort 3. The model correctly classified 17 of the 23 Cohort 3 stands as Cohort 3, but incorrectly classified 6 of the 23 Cohort 3 stands as Cohort 2 and none of the 23 Cohort 3 stands as Cohort 1.

The Combined Groups Map (Fig. 19) shows where the cohorts are located in the inference space formed by the two functions. It contains each of the cases and locates them around the centroid for each group.

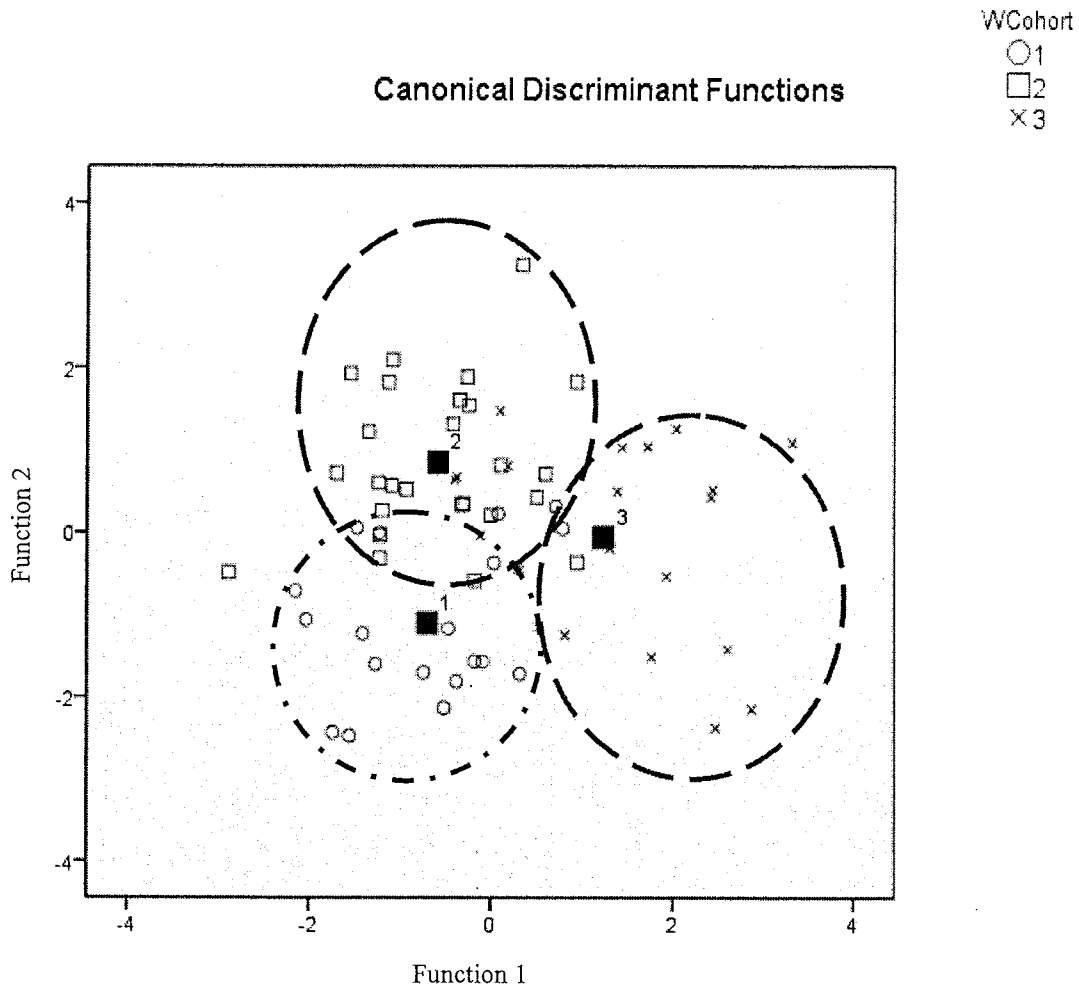


Figure 19. Combined groups map for all mixedwood stands of the CFI.

These results are for the entire set of stands found in the CFI data so that a comparison could be made between the total number of stands contained in cohorts 1, 2 and 3, and the number of stands in each cohort as predicted by the model. However, a further level of analysis is possible. The mixedwood stand type is known for each of the stands in the analysis, allowing for the stands to be sub-divided by mixedwood type. When examined by mixedwood stand type the model classified Cohort 1, 2 and 3 stands for MC1 mixedwoods with 79.3% accuracy, MC2 mixedwoods with 81.3% accuracy and MH1 mixedwoods with 65.2% accuracy (Tables 10, 11 and 12).

Table 10. Predicted versus actual Cohort status for MC1 stands from CFI.

		Weibull Cohort	Predicted Group Membership			
			1	2	3	Total
Count	1		8	2	1	11
	2		0	11	1	12
	3		0	2	4	6
%	1		72.8	18.2	9	100.0
	2		0.0	91.6	8.4	100.0
	3		0.0	33.3	66.7	100.0

Table 11. Predicted versus actual Cohort status for MC2 stands from CFI.

		Weibull Cohort	Predicted Group Membership			
			1	2	3	Total
Count	1		3	0	0	3
	2		1	2	0	3
	3		0	2	8	10
%	1		100	0.0	0.0	100.0
	2		33.3	66.7	0.0	100.0
	3		0	20	80	100.0

Table 12. Predicted versus actual Cohort status for MH1 stands from CFI.

		Weibull Cohort	Predicted Group Membership			
			1	2	3	Total
Count	1		3	1	1	5
	2		2	7	2	11
	3		0	2	5	7
%	1		60	20	20	100.0
	2		18.2	63.6	18.2	100.0
	3		0.0	28.6	71.4	100.0

4.4 TESTING AND VALIDATION OF PREDICTIVE MODEL USING PSP DATA

The predictive model which was constructed from the data contained in the CFI was tested with an independent data set contained in the PSP to verify its accuracy. The Weibull cohort classifications of the PSP plots are shown in Table 13.

Table 13. Weibull cohort status of PSP plots.

PSP STAND TYPE	NUMBER OF STANDS IN EACH WEIBULL COHORT			TOTAL
	1	2	3	
<u>MC1</u>	4	2	3	9
<u>MC2</u>	4	2	3	9
<u>MH1</u>	2	3	1	6
<u>Total</u>	10	7	7	24

The Combined Groups Map (Fig. 20) shows where the cohorts are located in the inference space formed by the two functions. Cohort 1 stands are distinguished in the model by having a lower score for both Equation 1 and Equation 2 (<50 and <10, respectively). These stands are clustered in the lower left quadrant of the graph. Cohort 2 stands scored in the mid-range for Equation 1 (between 45 and 55) but scored highly for Equation 2 (>8). They are clustered at the centre top of the graph. Cohort 3 stands scored highly for Equation 1 (>60) and lower for Equation 2 (<5). However, Cohort 3 stands were the least successfully predicted of the three cohorts.

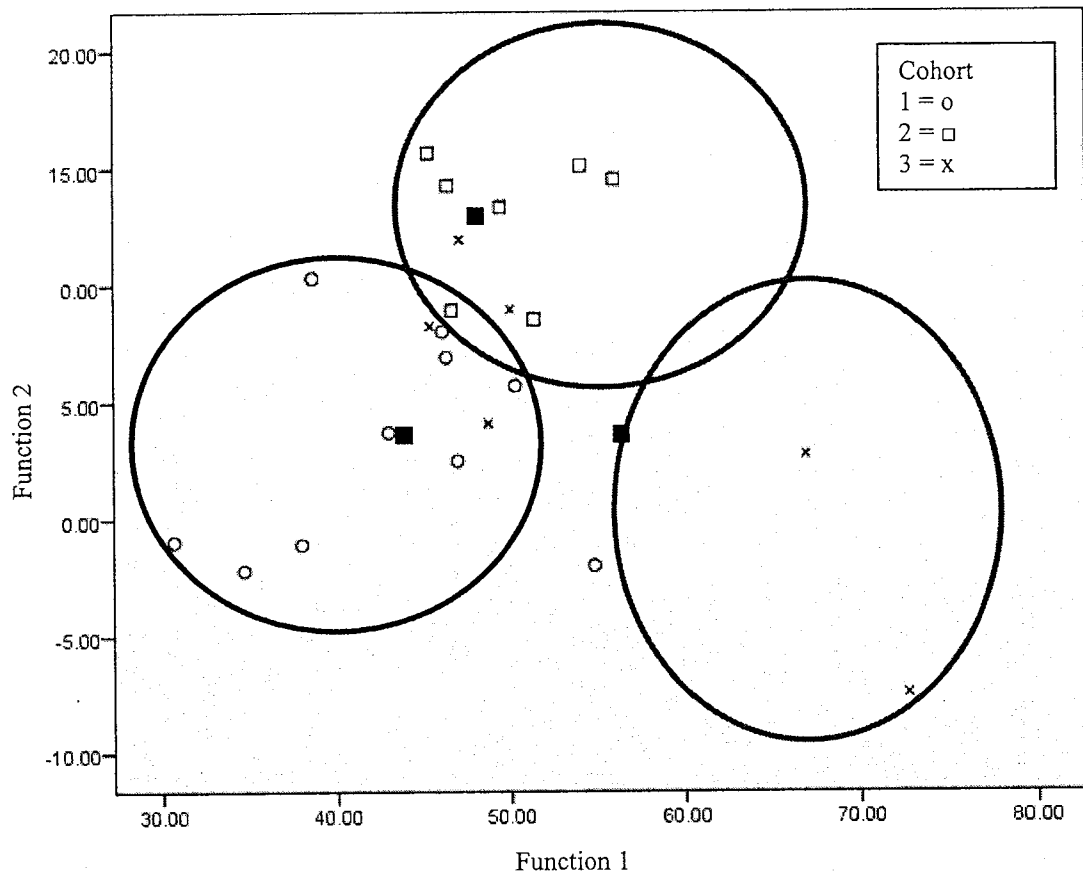


Figure 20. Cohort plot for all stands of the PSP.

The model correctly classified 79.2% of cases, with 90.0% of cohort 1, 100% of cohort 2 and 42.9% of cohort 3 correctly classified. The model: correctly classified 9 of 10 Cohort 1 stands as Cohort 1, but incorrectly classified 1 of 10 Cohort 1 stands as Cohort 2; correctly classified all 7 of 7 Cohort 2 stands as Cohort 2; correctly classified 3 of 7 Cohort 3 stands as Cohort 3, but incorrectly classified 2 of 7 Cohort 3 stands as Cohort 2, and 2 of 7 Cohort 3 stands as Cohort 1. By grouping Cohorts 2 and 3 together (Figure 21), a two-cohort version of the model could be used to discriminate between simple structured stands (Cohort 1) and complex structured stands (Cohorts 2 and 3) for

use in operational planning. Results for this 2-cohort model show Cohort 1 accuracy to be 90% and 85.7% for the combined Cohorts 2 and 3.

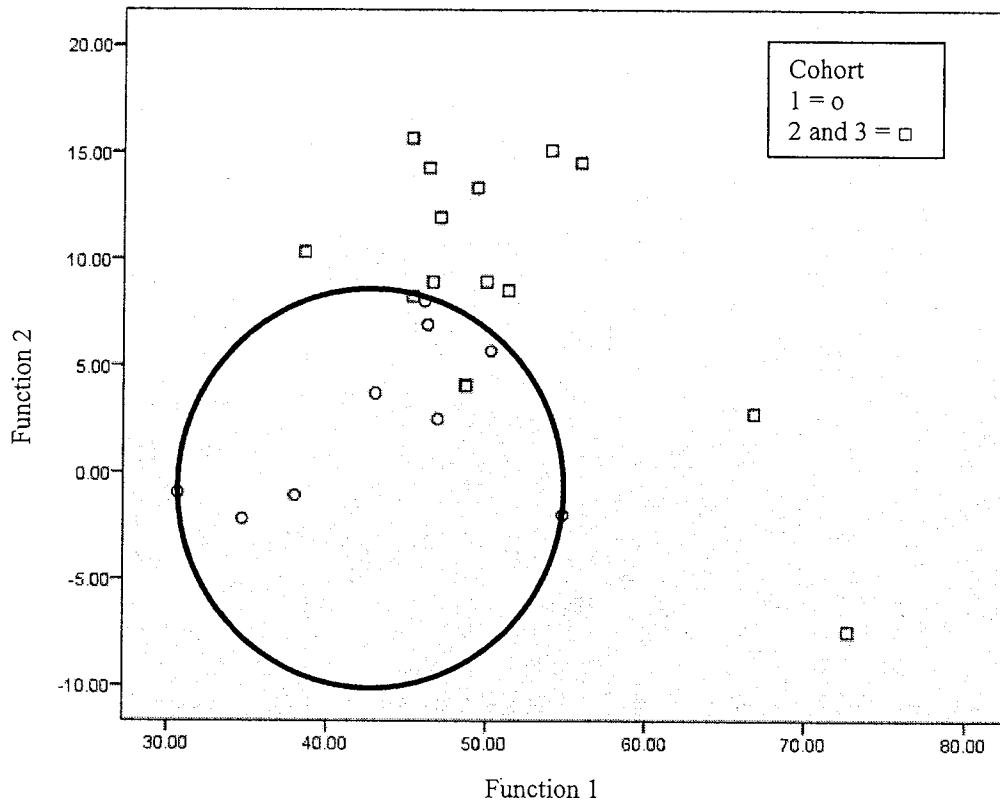


Figure 21. 2 Cohort 1 and combined Cohort 2/3 plot for all stands of the PSP.

5. DISCUSSION

The purpose of this study was to determine if boreal mixedwood stands in the Dog River Matawin Forest in northwestern Ontario could be classified into cohorts by discriminant function analysis of Ontario's standard FRI. Earlier work has shown that the diameter distributions of trees found within the stand differ in a predictable way between the three cohort classes. This study attempted to determine if other stand structural attributes also varied in a predictable fashion amongst the cohort classes. If the model proved capable of discriminating between the three cohort classes based on stand attributes contained within the FRI, then an operational stand map could be created which would link stand composition to stand structure in order to aid in the operational planning of forest management. However, an analysis of the FRI data showed that none of the variables gathered in a standard FRI (age, height, stocking and site class) was capable of any significant discrimination.

A site index is an ordinal representation of forest site quality based on the height of a dominant tree at a particular age. A site index is influenced by many factors such as soil (type, depth, moisture and nutrients), drainage and aspect. A site class assesses the capability of a site to sustain tree growth, as measured by a grouping of similar site indices to indicate relative site productivity. Site class may not be a significant indicator of cohort status because it is more suited to even-aged stands than uneven-aged stands and the data used in this study comprised a mix of both stand age types.

Stand stocking plays a large role in determining the horizontal structure of a stand and this, in turn, leads to an influence on the vertical structure. This study found, however, that the influence of stand stocking was not significantly strong enough to predict cohort classes in mixedwood stands.

Cohort classification has been shown to be significantly influenced by age and height in single species stands due the similarity of life traits exhibited by the component tree species in the stand (Boucher et al. 2003). Age and height are variables which would also seem to be applicable in determining the cohort classification of mixedwood stands. However, such was not the case in this study. In Ontario's standard FRI, age and height are recorded for the dominant species on the site, a fact that lessens their usefulness as classifiers of mixedwood cohorts. This is because mixedwood stands are, by their nature, composed of several species of trees, each with its own specific growth rate and life cycle. The heights and ages of dominant trees on sample sites result in different dominant species being measured at each site. This results in comparing the shade tolerant dominant trees of one site against the shade intolerant trees of another site. The very reason that age and height were found to be significant indicators in single species stands is because a single species allows for a benchmark height at a given age. Mixedwood stands have no such benchmark as each tree species grows at a different rate and so achieves a different height for a given age. The mixing of these differing rates within the stand works against the usefulness of age and height as discriminating variables in mixedwood stands.

Discriminant function analysis of the CFI data revealed three very highly significant stand variables for cohort classification: diameter class richness, coefficient

of variation and evenness. Diameter class richness is a count of the number of diameter classes found within the stand. A wide variety of diameter classes indicates a large range of tree sizes within the stand. This range of tree sizes contributes directly to the number of canopy layers within a stand because larger diameter trees, regardless of tree species, will tend to be taller and to be found in the overstory. Likewise, smaller diameter trees are more liable to be found in the understory. Therefore, a large range of tree diameter classes present within a stand is a good indicator of a large variety of tree heights and a range of canopy layers. Diameter class richness is based on the measurement of all trees within a plot and so gives a more accurate representation of the actual variation found within a sampled stand, as opposed to the measurements of just the dominant species found in the FRI.

Coefficient of variation is a measure of the standard deviation over the mean of diameter classes. As such it tends to be responsive to “clusters” of tree diameters, as would be found in the bi- or multi-modal tree distributions of Cohort 2 and 3 stands. Its usefulness in discriminating between the cohorts is based on the different clustering patterns of tree diameters found in the different cohorts. In the predictive model it can be seen that coefficient of variation is especially useful in discriminating between Cohort 3 stands and Cohort 1 and 2 stands.

Diameter Class Evenness compares the observed diversity of diameter classes to the maximum possible diversity of diameter classes that could be found within a stand. This measure of how evenly the tree diameters were distributed among the diameter classes in the predictive model proved capable of differentiating between Cohort 1 stands, which have relatively few diameter classes for the number of trees in the stand,

and Cohort 2 and 3 stands, which have a larger number of diameter classes represented within each stand.

This study has shown that diameter class data is essential in predicting cohort class status in boreal mixedwood stands. Cohort status can be determined and subsequently managed across the landscape as a tool for creating a variety of structures and preserving biodiversity through the application of silvicultural systems. While the concept of structural cohorts may introduce more complexity into forest management, it is a useful tool for maintaining structural diversity.

Discriminant function analysis of the CFI data has allowed us to create a predictive model that separates the stands into Cohorts. When this model was tested using the PSP data it was found that Function 1 of the model separates Cohort 1 from Cohort 3, a fact which is best illustrated in the combined groups plot of all mixedwood stands within the CFI. The horizontal distance separating the Cohort 1 centroid from the Cohort 3 centroid shows the discriminating power of this Function. The combination of Function 1 and Function 2 successfully distinguishes the centroid of Cohort 2 from the other two centroids. The overall accuracy of the model using data from the CFI was 75%. That is, the model correctly places a mixedwood stand into its correct Cohort 75% of the time.

It is useful to note that, in the construction of the model using CFI data, of the five misclassified Cohort 1 stands, three of them were incorrectly placed into Cohort 2. Also, of the six misclassified Cohort 3 stands, all of them were placed in Cohort 2. The difficulty in distinguishing between late stage Cohort 1 stands and early stage Cohort 2 stands, and late stage Cohort 2 stands and early stage Cohort 3 stands accounts for

almost all of the error found in the model results for CFI data. This problem illustrates the difficulty in trying to tease apart the classifications of Cohort 1 and Cohort 2 stands, and even more so for Cohort 2 and Cohort 3 stands. The main difficulty in the multi-cohort classification system is: when does a Cohort 1 stand stop being a Cohort 1 stand and become a Cohort 2 stand? Even visual observations of stands are likely to encounter difficulty when trying to classify a stand that no longer fulfills the requirements of a Cohort 1 but does not yet display all of the typical Cohort 2 features either. Stands that lie closest to the boundary edges between cohorts are the ones that are the most often misclassified. Other work has shown that dead standing trees can be significant in cohort classification (Kuttner 2007) and it may be possible that, when combined with the discriminating functions found in this study, they would prove capable of teasing Cohort 2 stands away from Cohort 1 and 3.

The model that was created using CFI data was then tested using the PSP data to gauge its predictive capacity. The overall accuracy of the model when tested against the PSP dataset was determined to be 79.2%. That is, the model correctly placed a mixedwood stand into its correct Cohort 79.2 % of the time.

When the accuracy of the model is examined by Cohort, a different picture emerges for the PSP than was found using the CFI data. The one misclassified Cohort 1 stand was incorrectly placed into Cohort 2. Also, none of the Cohort 2 stands were misclassified. However, the model correctly predicted Cohort 3 membership in only 42.9% of the cases, with two Cohort 3 stands being misclassified in each of the other two Cohorts.

The inability of the model to correctly classify Cohort 3 stands at much better than 40% accuracy need not be fatal to the utility of the model though. By grouping both Cohort 2 and Cohort 3 together, a two-cohort version of the model could be used to discriminate between simple structured stands (Cohort 1) and the grouped complex structured stands (Cohorts 2 and 3) for use in operational planning. Results for this 2-cohort model show Cohort 1 accuracy to be 90% and 85.7% for the combined Cohorts 2 and 3. The accuracy of this two-cohort model is a great improvement over the three-cohort model because it dilutes the model's inability to correctly recognise Cohort 3 stands by removing half of the incorrectly classified stands (those wrongly placed in Cohort 2 are no longer considered as errors.) Therefore, results for this new 2-cohort model remain the same for Cohort 1 accuracy (90%) but improve to 85.7% for the combined Cohorts 2 and 3.

This study focussed on classifying mixedwood stands that, by definition, contain more species than other stand classifications. Mixedwood stands are composed of a variety of species, each with their own growth rates, heights at maturity and time of introduction to the stand. Therefore, stand structural attributes such as age and height may be less effective at discriminating between mixedwood groups than between single species stands due to the range of each attribute across mixedwood groups. When taken as a whole, the stands that comprise the three mixedwood classifications represent a broad range of stand types with a broad array of stand attributes. Each individual mixedwood stand type, however, has a smaller range of variation within each attribute and so this smaller range may allow for increased discrimination.

6. CONCLUSIONS

Stepwise discriminant function analysis of the boreal mixedwood stands found in the Ontario standard FRI for the Dog River-Matawin forest failed to reveal any variables capable of significantly discriminating between cohorts of the multi-cohort forest management model. The types of information collected in a standard FRI are insufficient to allow for successful classification.

Stepwise discriminant function analysis of the same stands using data collected during Bowater's CFI revealed three variables capable of significantly discriminating between cohorts: Diameter Class Richness, Coefficient of Variation and Evenness. The model built using CFI data correctly classified mixedwood stands into the cohort classes in 75% of the cases. The analysis produced a predictive model with two Functions: Function 1 was capable of successfully discriminating between Cohort 1 stands and Cohort 3 stands, while the combination of Functions 1 and 2 was capable of discriminating between Cohort 2 stands and Cohort 1 and 3 stands.

The validation test of the predictive model using PGP data revealed that it was capable of discriminating between the Cohorts in 79.2% of the cases. The model was able to successfully classify Cohort 1 stands and Cohort 2 stands, but was less able to classify Cohort 3 stands. Model accuracy was improved when a two-cohort approach was applied, using Cohort 1 (single structured cohort) and a combination of Cohorts 2 and 3 (complex structured cohort). The difficulty experienced by the model in successfully predicting the Cohort 3 status of the PSP stands was partially alleviated by

the fact that several of the Cohort 3 stands were incorrectly placed in the Cohort 2 group. Therefore, when the Cohort 2 and 3 groups were combined those previously misclassified stands became correctly classified as complex structured stands. This accounted for the increase in accuracy when the complex structured stands were combined into a single Cohort.

These results point to the possibility that a broad-based tool might be developed that would include other stand attributes (e.g. snags) in order to classify mixedwood forest stands based on forest regions. For example, further refinement of this model might lead to a method for classifying mixedwoods across all of northwestern Ontario, based on some of the variables derived here and a few others that could be gathered during Forest Resource Inventories, Permanent Growth Plots or Permanent Sample Plots. This would allow for the classification of large numbers of stands within a landscape without having to rely on extensive re-measurement. Suggestions for additional variables to be added to FRI data would include tree diameters and dead standing trees.

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APPENDIX I (on disc).

This Appendix contains the Master lists for analysis including the raw data for each stand and plot used in the study, as well as the converted data and derived stand variables, on Microsoft Excel spreadsheets.

APPENDIX II (on disc).

This Appendix contains the SPSS input and output files for the DFA analyses including tables, graphs and plots.