MODELING SOUTHWESTERN PONDEROSA PINE FOREST ECOSYSTEM MANAGEMENT IN A SPATIO-TEMPORAL MULTI-OBJECTIVE DECISION-MAKING FRAMEWORK

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A Dissertation

Submitted in Partial Fulfillment

of the Requirements for the Degree of

Doctor of Philosophy

in Forest Science

Northern Arizona University

August 2007

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UMI Number: 3273747

UMI Microform 3273747

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ABSTRACT

MODELING SOUTHWESTERN PONDEROSA PINE FOREST ECOSYSTEM MANAGEMENT IN A SPATIO-TEMPORAL MULTI-OBJECTIVE DECISION-MAKING FRAMEWORK

BORIS POFF

Forest ecosystems are a unique complex of faunal, floral and physical structures with numerous cultural, social, economic and environmental components interacting with one another. The management of such a system often involves multiple interests and stakeholders, with different and often conflicting expectations and objectives. Today's ecosystem management requires the ability to accommodate commercial as well as non-commercial objectives, both quantitative and qualitative, and respond to social, political, economic as well as cultural changes.

Spatial and dynamic computer programs are combined with a Multi-Objective Decision Making (MODM) technique using multiple forest management objectives to provide spatio-temporal solutions for a forest ecosystem management problem on a landscape scale. Forest management objectives are related to forest stand density as the decision variable, expressed in basal area, using response functions and Compromise Programming (CP). CP is the MODM component of the modeling effort presented in this dissertation, while the USDA Forest Service Forest Vegetation Simulator (FVS) and ArcGIS are the temporal and spatial components, respectively. In the ModelBuilder module of ArcGIS 9.1, the decision variable output of FVS is displayed spatially and is assigned a CP achievement level that is an indicator of how well a forest stand meets the best possible solution given all management objectives.

Displaying the achievement level spatial as it changes through time provides a mechanism for solving a dynamic and spatially varied multi-objective problem at the landscape level, in order to equitably address various forest resource components and their interaction in a holistic and sustainable manner. Since the ponderosa pine forest in the Southwest is currently above its historical stand density, the study identifies numerous feasible forest management alternatives expressed in terms of changes in vegetation density with time and space.

The model effort presented in this dissertation provides valuable information for project managers in their ecosystem approach to forest management. For example, the model output can be useful to demonstrate long-term treatment effects on wildlife, forest fire, grazing and recreation and other forest ecosystem components and help forest managers analyze trade-offs and justify their management decisions. It is also a tool that can be used in the planning stages and the decision process of forest wide management actions.

ACKNOWLEDGEMENT

I would like to that my dissertation committee members, Aregai Tecle, Brian Geils, Dan Neary and Ray Huang, for their contributions. Further, I would also like to thank Dick Fleishman and the Upper Beaver Creek Fuel Reduction Project Interdisciplinary team members for their willingness to share their data with me.

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To Jeri
And Tom too

CHAPTER 1- INTRODUCTION

1.1 BACKGROUND

Public policy in the United States of America, and around the world, has begun to mandate that we manage our forests as ecosystems (FEMAT 1993, Covington et al. 1997, Costanza et al. 2002). Managing a forest as an ecosystem requires consideration of interacting components of the whole system simultaneously rather than by taking single resources such as timber, water, wildlife, ranges or mineral resources extraction individually. A forest ecosystem should be managed for purposes that include aesthetic quality, biomass, timber, forage for livestock or wildlife, the quantity and quality of water, reduction of fire and flood hazards, recreational use, extraction of mineral resources, wildlife habitat protection, carbon sequestration, promotion of healthy interaction between components, controlling insects and diseases or invasive exotic plant species. Many of these ecosystem components are connected either sequentially or geographically, or both; and their interactions may be complementary, supplementary or competitive, suggesting an integrative and holistic approach in order for the management of the system to be successful.

In terms of today's resource management, risk and uncertainty in the planning and decision-making process can not be separated from complex social conflicts and the dynamics of landscapes and ecosystems (Borchers 2005). Many believe that risk and uncertainty are intrinsic in the behavior of complex systems and can not be reduced by science (Allen and Starr 1982, Cillers 1998, Levin 1998 and 2002). However, our past experience can be drawn upon to guide our understanding of ecosystem responses to resource management actions. While there is not perfect certainty of how management actions will ultimately affect future conditions, an educated guess can be made as to how actions today will manifest themselves in the future.

Human activities have altered forest ecosystems resulting in new management objectives as well as new challenges for which we have no prior experience. In the forests in northern Arizona in particular, high grading has reduced the gene pool of healthy trees by harvesting the tallest and biggest trees (Raish et al. 1997). Fire suppression has allowed fuels to accumulate in the forests and has thereby increased the risk of catastrophic wildfires (Covington et al. 1994). Hunting and changes in habitat conditions have changed the dynamics of predator and prey relationships The elimination of many predators, such as wolves and bears, has allowed prey species to increase. Urbanization and human encroachment along the wildland urban interface (WUI) are leading to habitat fragmentation. Increased human presence in the WUI has amplified the potential for human caused fires to spread into the wildland and with that the loss of many of the benefits of natural forest ecosystems. On top of that climatic changes will possibly alter ecosystems, their functions and responses to human management actions.

Many of the forest management objective and ecosystem components mentioned above interact on multiple levels with one another through space and time. This interaction increases the complexity of the framework within which they are managed. This complexity requires the design of new and better forest management approaches. One approach is a spatial-temporal multi-objective decision analysis to address components of the forest ecosystem simultaneously through space and time in fair, transparent and equitable manner. An objective, transparent and just management approach is needed not only because it is the "right thing" to do, but because there is a general distrust in the Federal government and its bureaucratic decision-making processes. Numerous legislative acts and laws have mandated public input and are aimed at limiting the decision-making discretion of federal land management agencies, such as the USDA Forest Service (USFS). Since, individuals, businesses and environmental NGOs have used legal recourse as part of the land-management process. However, the public is looking for ways that are less legalistic and technical to engage the USFS in their decision-making processes. The modeling effort presented in this dissertation provides such an avenue to present the "nuts and bolts" behind the USFS's decision-making process in a clear, objective and transparent manner.

Different objectives considered herein may represent needs and/or wants of a single decision-maker or the wishes and aspirations of various decision-makers that have different and often conflicting interests in the way an ecosystem is managed. Generally, this approach to forest management has been either absent or merely been given "lip service" due to long standing perceived insignificance of the problem. Even though humans have been part of forested ecosystems for over at least thirteen thousand years in northern Arizona (Coder 2000), the human presence and effects have drastically increased over the past century. While some activities such as people recreating in the forest are more recent and have mostly short-term impacts; other situations, such as timber harvesting, road building or mineral resource extraction have long-term impacts that will be with use for at least several centuries more.

A multi-objective decision making (MODM) model should be based upon some desired future conditions of forest ecosystem components, such as timber yield, wildlife habitat, water yield, water quality level, fire hazard reduction, and other qualitative values of forest ecosystems. These desired condition, which are usually determined by land managing agencies with *some* public input, are evaluated with respect to many independent or a mix of management actions (i.e. mosaic of varying levels of vegetation reduction – at least in northern Arizona) to achieve the desired conditions through time. The later recognizes that the conditions produced through management actions are not static. For example, if there is a 120-year planning horizon, the desired conditions might be achieved in the initial years, but the conditions several years later may become undesirable. Therefore, it is important to have the ability to accurately model (given certain risks and uncertainties) the impacts of forest management activities on various forest components dynamically.

In addition to addressing temporal distribution, a MODM approach to forest resource management also needs to address spatial changes to forest conditions. Landscapes such as forest watersheds can be identified at various scales (Montgomery et al. 1995). While a forest management unit may consist of a stand or a watershed in some of the historic land management computer programs such as FORPLAN (Hof and Joyce 1992), an ecosystem approach to forest management should be viewed at a landscape scale such as a large watershed within a National Forest (i.e. the Upper Beaver Creek Watershed, as used for the case study in this dissertation) or even the entire ponderosa pine forest in the Coconino National Forest. The main reason for this is that many physiological and biological processes and relationships do not coincide with land management unit boundaries. In the past, forest management strategies, which were mostly concerned timber harvesting, minimally considered non-timber outputs in their spatial planning of the harvesting prescriptions. This was primarily achieved by avoiding adjacencies. The management constraint of non-adjacency refers to the concept that one management unit (i.e. a stand or watershed) can not be harvested within a given timeframe, if an adjacent management unit had been harvested within a given number of years. However, Hof and Bevers (2000) point out that *avoiding adjacency of management actions may actually be counter-productive for connecting wildlife habitat patches, creating edges, controlling the spread of exotic pests, managing water flows or in managing spatially-defined uncertainty*. While adjacency could be avoided by conceptually simple linear programming algorithms (Hof and Joyce 1992), computing power in the early 1990 made such algorithms impractical. For example, a grid or matrix with 25 management units (or cells) and two management actions give 33 million possible spatial configurations (Hof and Joyce 1992). While in 1992 this seemed a monstrous calculation even for fast a computer, it takes minutes if not less today. Our spatial software today allows us to look at adjacency with deterministic models, such as Inverse Distance Weighting and Radial Basis Functions, as well as probabilistic techniques that also take spatial autocorrelation into consideration, such as Kriging and Cokriging.

With the temporal and spatial forest planning software available today and considering the complexity and number of variables involved in ecosystem management, it is appropriate to use a spatio-temporal MODM approach. A model that can be used in such a framework, however, should be seen only as a tool in the greater concept of adaptive management. Adaptive management should treat management interventions as experiments to learn from, as opposed to solutions, and avoid taking action with just one objective in mind (Gunderson and Holling 2002). Further, adaptive management requires monitoring. While models are used to mimic, in a rather simplified fashion, what happens to an ecosystem through space and time, unanticipated events, such as wildfires, will have unforeseen consequences. Also changes in administrations and leadership in land management agencies might result in changes of management goals. Direction changes can also be prompted by new understanding of resources within the ecosystem dynamics as well as new social demands. So in order for long-term plans to be successful, they should be updated every 5 to 10 years to accommodate new information and new direction (Olson and Orr 1999).

1.2 PURPOSE OF STUDY

The purpose for this study is two-fold: (1) to formulate a complex forest ecosystem management problem in a spatio-temporal multi-objective decision-making framework and (2) to solve a case study-problem to validate the spatio-temporal MODM modeling effort and determine its suitability to forest-ecosystem management.

The forest ecosystem in northern Arizona has been exploited for its market-oriented commodity values over the past century. These values mostly include livestock production and timber harvesting, primarily old growth. Such uses in combination with the exclusion of the natural fire regime have lead to serious degradation of this ecosystem (Covington et al. 1997). Frequent low-severity wildfires had been part of the ponderosa pine (*Pinus ponderosa*) forests and other ecosystems in Northern Arizona. Overstory and understory vegetation, as well as the other components of the ecosystem, have adapted to this regime. Low precipitation rates cause dead woody debris to decompose very slowly. However, under natural conditions, this debris is burned up on a regular basis by frequent low-severity fires and does not accumulation much in this forest system. Further, the frequent fire regime kept the regeneration of new trees in balance with the dying of old trees. However, federal government fire suppression policies disrupted this process and brought tree density to unprecedented high levels. The situation created the necessary circumstances, in the form of fuel accumulation on the forest floor and ladder fuels, for catastrophic wildfires to occur easily and more frequently than it would have under natural conditions. When such a wildfire event, as the Rodeo-Chediski fire of 2002, occurs, it can become catastrophic with negative impacts at many levels. For one, hot and severe fire burns deep into the soil and affects seed viability, microorganisms, organic content, as well as the availability of nutrients (Neary et al. 2005). Such a hot fire easily changes soil conditions, affecting its water-holding capacity, destroying seed-bearing trees and seed banks in the ground and in the process it lowers the ability of the ecosystem to renew itself. In other words, the resilience of the ecosystem is reduced by the suppression of naturally occurring disturbances. Next to the combustion of forest vegetation during a wildfire, the most destructive impact of a wildfire comes from post-fire flood peak flows. These flows can severely affect stream physical conditions, aquatic habitat, aquatic biota, cultural resources and human health and safety. When these wildfires are located in or near the WUI, homes and other structures are destroyed by the fire, leading to direct economic losses. Indirect economic losses can also occur from the destruction of recreation areas, when recreationist no longer want to, or can, visit places burned over in a fire.

The extreme droughts and forest fire seasons in the beginning of this century demonstrate that tree stand density in the northern Arizona ponderosa pine forests needs treatment to reduce fire hazards and improve forest ecosystem health. The level to which the forests should be treated to promote a balanced ecosystem still remains highly controversial. One approach declares that it would be advantageous to reduce stand densities to pre-European settlement levels (Covington et al. 1997). However, others have argued that not only the forests and social needs have changed in the past century but society and its demands on the forest have increased drastically and that a different basis for forest treatment would be preferable (Wagner et al. 2000). Some of these changes include disappearances of key species and the threat of extinction for others, climate fluctuations, invasion of exotic species, human population explosion and changes in technology. All these changes may affect the way our forests should be managed. Moreover, managing a forested ecosystem often involves stakeholders that have different interests in the biophysical, social, cultural and spiritual elements of the forest. Again, the ponderosa pine forest ecosystem in northern Arizona has a complex structure consisting of numerous components that interact with each other to form a unique functioning system.

According to Gunderson and Holling (2002) ecosystems are a part of the solution: *Natural systems have great resilience because of diversity within functions and across scales.* Humans have the potential of foresight and the ability to learn and do the right thing, that is why *bad regional policy and management can typically be corrected, but at a great and often increasing costs* (Gunderson and Holling 2002). Besides increasing restoration costs, ecosystems are not infinitely resilient. Hence, forward-looking management models are needed that can let land managers know how management actions will affect various forest ecosystem components and social values. This study develops such a modeling effort on the basis of previous works (Brown et al. 1974, Tecle et al. 1998, McMahan et al. 2002, Poff 2002, Brimicombe 2003).

Once an ecosystem is degraded or becomes unhealthy, as it is the case with the ponderosa pine forest ecosystem in northern Arizona there are three options: (1) The first is no action alternative speculating that the forest ecosystem will return to some acceptable state by itself in the face of continuously changing social and environmental conditions. Given the state of fuel accumulation, diseases and pathogens, drastic climatic fluctuations, soil erosion rates, this would most likely occur in geologic time. (2) The second option is to admit that the state of the ecosystem is beyond financial, political or physical capacity to restore and therefore adopt management strategies to this new, altered system. (3) The third option is to actively manage the ecosystem and restore it to a desirable state compatible with on-going social and environmental trends. If a primary management goal is to maintain and leave a healthy forest ecosystem for future generations, than the only acceptable option is number three.

In this dissertation, spatial and dynamic computer programs are combined with a MODM technique using multiple forest management objectives to come up with spatio-temporal solutions for a forest ecosystem management problem on a landscape scale. This is achieved by relating forest management objectives to forest stand density as the decision variable, expressed in basal area, using specially developed response functions as well as Compromise Programming (CP). CP is the MODM component of the model, while the USDA Forest Service Forest Vegetation Simulator (FVS) and ArcGIS are the temporal and spatial components of the model, respectively. In the ModelBuilder module of ArcGIS 9.1, the decision variable output of FVS is displayed spatially and is assigned a CP achievement level, which serves as an indicator of how well a forest stand meets the best possible solution given all management objectives. Since the ponderosa pine forest in northern Arizona is currently above its historical stand density, this study identifies numerous feasible forest management alternatives expressed in terms of changes in tree density with time and space.

The proposed approach is needed for several reasons. First it is not necessary to automatically restore the forest ecosystem in northern Arizona to some time in the past, because the number of people and their needs, as well as the needs of other animals, from the forest environment have changed in the past 150 years. But it is crucial that the resilience of the forest ecosystem in northern Arizona is restored to its "natural" level and maintained in a sustainable manner otherwise we might lose the ponderosa pine forest ecosystem. However, if a model exists that decision makers can use to successfully determine how certain management actions, in terms of vegetation manipulation, attempt to meet a multitude of management objectives simultaneously over space and time, it may be able to help decisions that preserve the forest ecosystem here in northern Arizona, while mimicking or allowing fine-scale adaptive cycles to occur. While this will not maximize everybody's wishes, it can at least satisfy the needs of all concerned stakeholders. To validate the modeling effort and demonstrate its applicability, the Upper Beaver Creek Fuels Reduction Project in the Coconino National Forest in north-central Arizona is used as a case study.

1.3 STUDY SITE

The Upper Beaver Creek Watershed Fuel Reduction Project (UBC) is located in north central Arizona, about 50 km (30 miles) south of Flagstaff. The project area encompasses about 19,340 ha (49,123 acres) on the Mogollon Rim and Red Rock Ranger Districts of the Coconino National Forest. The UBC area includes several developed and undeveloped private lands, and special use areas within the Wildland-Urban Interface (WUI). The designated WUI area encompasses about 6,715 ha (17,057 acres). The project area lies in the middle of the southwestern ponderosa pine forest and can be viewed as a good representation of the entire ponderosa pine ecosystem.

1.4 ORGANIZATION

This dissertation is organized into five chapters. The current chapter provides the setting into which this modeling effort comes to play and Chapter 2 presents a comprehensive overview of the applicable literature. The following three chapters are written as independent articles for publication in peer reviewed journals. Chapter 3 describes the mathematical aspects of the multi-objective decision making framework in detail. Here the equations of Compromise Programming and the related response functions are explained. A step-by step problem formulation guides the reader through the procedure of how to set-up forest management in a spatial-temporal MODM framework. Chapter 3 includes a sensitivity analysis of the MODM technique used and it determines the best methods to be used in the later chapters. Results are presented in a conceptual context. Chapter 4 describes the interactions of the different tools and techniques used in the modeling effort in the language of a systems analyst. While real data from a case study are used, the application of a spatio-temporal MODM model is discussed in a conceptual context. In Chapter 5 a case study is presented of how the model can be applied when managing a landscape scale project. In this chapter, data specific to management of Upper Beaver Creek Fuel Reduction Project are used. The chapter incorporates the aspirations of the decision makers for this particular landscape management project. The last chapter contains a summary of the lessons learned in this study and the conclusions drawn from it. Also it includes some recommendations for further studies to address various kinds of forest management scenarios that use different decision variables as well as incorporate the other forest ecosystem components. Management recommendations are provided as well.

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CHAPTER 2 – LITERATURE REVIEW

An essential requirement to solving a problem is its complete understanding. The aim of this chapter is to review the literature to have a good understanding of the different components, their interactions in time and space and how they can be managed in a multi-objective framework. Even though the conceptual model described in this dissertation may be applied to any type of forest ecosystem, the focus of this study is specifically on the ponderosa pine forest ecosystem of the southwestern U.S.A. This chapter begins with a brief description of the southwestern ponderosa pine forest ecosystem, followed by a short historical look at two modeling software, namely the Forest Vegetation Simulator (FVS) and Geographic Information System (GIS), as well as their applicability to the management problem laid out in this dissertation. In the following sections of this chapter "spatial representation and temporal dynamics" and "spatial distribution and landscape modeling" are discussed. In the next section multi-objective decision-making (MODM) and as it relates to the above is reviewed. In the last section this chapter is summarized.

2.1 THE SOUTHWESTERN PONDEROSA PINE FOREST ECOSYSTEM

The southwestern ponderosa pine forest ecosystem is considered the largest continuous stand of ponderosa pine (P*inus ponderosa* var. *scopulorum*) in the U.S. and it stretches from southern Utah through northern and central Arizona to south central New Mexico. It constitutes about half of the 6.5 million ha of ponderosa pine forest ecosystem in the Rocky Mountains (USDA Forest Service 1989). Over 65% of the forest system is under National Forest Ownership (Conner et al. 1990). The forest forms an irregular but solid belt of 480 km in length. Regional climate and localized physiographic conditions have contributed to the shape of the forest and the distribution of the trees along the rain-graced highlands and mountains of this region (Schubert 1974). Annual rainfall ranges from 48 to 63.5 cm (Fox et al. 1991). Generally, this forest is found at elevations ranging from 1800-2700 m above sea level, with a much higher altitudinal distribution on north-facing slopes compared to south-facing slopes. Vegetation zones in the Southwest tend to be vertically arranged in an altitudinal moisture and temperature gradient, which demonstrates the effects of aspect and elevation on the biotic communities (Lowe 1964). The current distribution of ponderosa pine is mostly affected by climatic factors, such as precipitation and temperature gradients, as well as fire regimes; however, anthropogenic influences such as grazing and fire-suppression have also some influence on its distribution (Covington et al. 1997). Past overgrazing practices have led to the deterioration of grass covers and allowed tree species, such as ponderosa pine, to become established in former grasslands (Fox et al. 1991). Some wildlife species, however, have benefited from dense vegetation, such as wild turkey (*Meleagris gallopave*), elk (*Cervus elaphus*) and deer (*Odocoileus* spp.). While these species require management practices that maintain this density to provide nesting, bedding, hiding and escape cover (Wagner et al. 2000), this same dense vegetation presents a management problem for reducing the risk of wildfires, and the spread of tree diseases and pathogens. Managers of the ponderosa pine forest ecosystem are often asked to achieve specific societal objectives within ecological and economic constraints. Often these objectives, as described above, require conflicting management actions, hence a multi-objective decision making tool, as described in this dissertation is pertinent.

2.2 FOREST VEGETATION SIMULATOR

The USDA Forest Service's Forest Vegetation Simulator (FVS) is a large-scale forest management tool that has been developed over a period of 30 years and is a product of continuing collaborations by hundreds of contributors (Dixon 2002). FVS has its roots in Prognosis (Stage 1973), which was basically an elaborate tree growth model. Originally, Prognosis was conceived for use in the Northern Rocky Mountains, but as it became more inclusive and elaborate, it was renamed "Forest Vegetation Simulator" after models developed for other regions, such as TWIGS (Miner et al. 1988) and GENGYM (Edminster el al. 1991) were incorporated into it (Dixon 2002).

Today various United States government agencies, such as the USDA Forest Service, the USDI Bureau of Land Management and Bureau of Indian Affairs, as well as industry, educational institutions and private landowners use FVS extensively for predicting forest stand dynamics (Dixon 2002). FVS can be utilized to summarize current stand conditions, predict future stand conditions under various management alternatives and its output can be input into forest planning models as well as other analysis or spatial tools such as geographic information systems (GIS).

McMahan et al. (2002) introduced the FVS Event Monitor ArcView® Project (FVS-EMAP). This tool allows users to move simulation results from FVS into a GIS format. With FVS-EMAP users can display FVS variables for a multi-stand landscape through time. This breakthrough in technology is partly based on the advances made by Crookston and Stage (1991), who developed the Parallel Processor Extension (PPE) in FVS. This program takes into account the spatial interactions between adjacent stands and permits the simulation of stands altogether (in parallel) through time, instead of one stand after another (in series). While some events, such as disturbances, are not available in off-the-shelf FVS models, customized results can be imported into GIS and be displayed spatially, by treatment alternative and over time (Maffei and Tandy 2002). Projected variables for each stand within a landscape can be tied to GIS and mapped spatially so users can view the projected outcomes over time. Hummel et al. (2002) used FVS to evaluate the contribution of stand level treatments to achieve landscape goals in combination with integer optimization techniques and found that PPE has limitations that affect its usefulness. This is because spatial analysis of all possible treatment combinations requires techniques not available in PPE. Instead Hummel et al. (2002) used heuristics (Reeves 1993) to integrate FVS with an optimization algorithm to derive benefits from both simulation and optimization techniques. However, their optimization only identified efficient solutions that allowed testing for complementary or competitive relations between two goals over time and space. Nonetheless, the authors were able to use resource values as input to the optimization algorithm that identified the schedule for each unit that best achieved their landscape goals, when all units were evaluated together in each interval. Padgett et al. (2002) demonstrated that the results of landscape level vegetation projections differ in FVS depending on the technique used to collect the data that are input into the model. They found that unaggregated data best represented the fundamental ecological processes and gave the most realistic projections of size and density distributions over the landscape.

To address uncertainty, Hummel et al. (2002) used the western root disease (Frankel 1998) and fire models (Beukens et al. 2000) to incorporate stochastic events in FVS. These techniques resulted in different realization of stand development for the same initial tree list. In addition, the model of mistletoe dynamics linked to FVS as described and developed by Robinson et al. (2002), addresses sensitivity analysis and uncertainty. Other possible sources for uncertainty in FVS are sampling, human and technical errors. According to Padgett et al. (2002), FVS is the best and most comprehensive model for landscape scale evaluation of forest responses to management alternatives because it uses metrics in vegetation modeling, such as tree size and density.

2.3 GEOGRAPHIC INFORMATION SYSTEM (GIS)

Computer technology, hardware and software, such as FVS and GIS, have revolutionized land management decision-making capabilities. This surge in technology coincided with the recent shift in the focus of forest management from emphasizing stands to prioritizing landscapes. Some believe that the availability of GIS has been a key factor in landscape analysis (Smith et al. 2002). Ian McHarg probably used the first analog version of GIS for ecological planning purposes (McHarg 1969). Transparent maps were stacked on top of each other over a single light source. Each map had a darker area representing various areas of interest or impact of spatial factors, such as groundwater. The lightest areas were then identified as having the least impact. Early digital versions of GIS were topological models providing adjacency and connectivity information. These models were originally developed for the Canadian Geographic Information System in the mid-1960, but were also used by the United States Bureau of the Census DIME project for the 1970 census (Goodchild 2005). Other GIS models were developed by the Harvard Laboratory for Computer Graphics and Spatial Analysis in the late 1970s, and Environmental System Research Institute (ESRI) in the early 1980s.

These models were designed *to represent a portioning of two-dimensional space into nonoverlapping and space-exhausting polygon*" (Goodchild 2005). The first digital GIS models in natural resource management were data base management systems with very simple mapping capabilities, such as TIMBER-PAK (van Roessel et al. 1978). But it was from the early 1990s onward that there has been an increased and accelerated interest, research and application of GIS in natural resource modeling (Brimicombe 2003).

The middle of the first decade of the new millennium is finally witnessing the beginning of the integration of comprehensive spatial analysis and modeling on a single platform with the capability for geographic data management, analysis and visualization (Maguire 2005). This breakthrough is partly due to advances in computer hardware and software engineering and in part due to a growing interest and understanding of spatial analysis and modeling in the social as well as environmental sciences. However, dynamic system simulation, research optimization in operations and visualization of multidimensional data are still neglected areas (Maguire 2005). One of the most effective ways of communication remains the visual domain. This is especially true when communicating a spatial problem to variety of stakeholders and decision-makers, particularly when the problem at hand can be represented digitally (Batty 2005). Because GIS systems are intrinsically visual, we can clearly and simply represent Euclidian space in two and three dimensions.

In GIS, there are basically two different ways of integrating a general-purpose model: (1) a GIS-centric approach and (2) a simulator-centric approach (Miller et al. 2005). A general-purpose dynamic modeling tool is a high level programming language, which a user can employ to define equations describing how a system, such as a forest ecosystem, can evolve over time. The user provides the equations necessary to model the system, but the model itself has no specific built-in knowledge of the system that is being modeled. In a GIS-centric approach, the GIS software provides the primary interface and data access tools. Here, the user primarily interacts with the GIS software. In a simulator-centric approach, the simulation software provides the interface and data access tools with which the user would typically run the simulation. An example of the first would be the ESRI ArcGIS ModelBuilder, which allows the user to build a model using a diagram that resembles a flowchart (Krivoruchko and Gotway-Crawford 2005, Maidment et al. 2005, Miller et al. 2005). In this feature of the ArcGIS software, the model consists of a set of spatial processes that convert input data into an output layer. ModelBuilder version 9.1 is not dynamic, temporal components can be simulated by running the model multiple times as script, using a regular time step (Miller et al. 2005). Another possibility would be to embed a dynamic simulation model, such as FVS, in the ModelBuilder as a process node. Here, the user would select data objects that are linked to any type of GIS data, such as forest stand data that define the input data to the simulation model process node. In a simulation-centric approach, a simulation model, such as a tree growth model, provides data that could be applied to different locations. The user of the simulation software would create a submodel representing a generic template for a particular GIS object (such as a grid cell). This grid cell than would define the properties and dynamic behavior of a system at a generic map region.

2.4 SPATIAL REPRESENTATION AND TEMPORAL DYNAMICS

Modern GIS software provides a consistent and mature technology for storing, organizing, retrieving and modifying information on the spatial distribution of plants, forests, land use, land parcels and many other natural resources and anthropogenic features (Burrough and McDonnell 1998). Although GIS offers a well-established and well-defined framework for the analysis of spatial component of geographic problems, support for the analysis of the temporal or dynamic component of these issues is largely lacking (Burrough et al. 2005). Yet, many central problems in modern ecology are best investigated by means of dynamic simulation models (Sklar and Costanza 1991).

While GIS has advanced by leaps and bounds over the past two decades, the question of how we must deal with time and space has paralleled its development and has raised the demand for close collaboration between GIS and mathematical modeling (Peuquet 2002). Static models often are used as indicators, combining various inputs to create a useful output (Goodchild 2005). For example, mapping tree density, canopy closure, downed woody debris, slope and other forest stand properties will give us estimates about the geographic variation and vulnerability of forest stands to fire potential, again based on mapped properties. Dynamic models, however, represent a process that modifies or transforms some aspect of the forest through time. For example, dynamic models of streamflow are used to predict changes in flow magnitude through time (Goodchild 2005). Even though dynamic simulation models today are used in fields ranging from biology to engineering and business, most of them are not designed to simulate geographically-distributed systems, because applying a general purpose simulation model as a geographic system is very difficult, making dynamic GIS modeling currently more a concept than a practical reality (Miller et al. 2005). Most spatial models do not deal with dynamic processes per se. Instead they measure, analyze, and simulate associations and relationships with variables at a cross section in time between multiple points through time (Batty 2005).

Burrough et al. (2005) define a dynamic spatial model *as a mathematical representation of a real-world process in which the state of a geographic field or object changes in response to variations in the driving force.* Over the past ten years, GIS toolkits have been developed to address many of the generic aspects of space-time modeling, such as PCRaster (Burrough et al. 2005). However, *many scientists have approached the problem of modeling dynamic aspects of environmental processes by writing individual models using standard languages such as FORTRAN and C++, which could be interfaced with GIS. These models are often difficult to maintain and modify, particularly if the original author is no longer working in the team* (Burrough et al. 2005).

Yet, it is important to include a time component in the analysis of environmental problems, where pattern changes are a response to external forces, such as land cover or land form changes (Burrough et al. 2005). Further, any system that models the space-time process "must include procedures for discretizing space-time and for the computation of new attributes for the spatial and temporal units in response to the driving force" (Burrough et al. 2005). It is also essential to choose the correct spatial and temporal resolution, because variations that occur within the dimensions of the cell will not be registered by either the data or the process. Temporal changes in attributes of cell values can be computed for single cells or for neighborhoods of varying size and shape. Once a model is set up and run, the changes can be visualized as a film, providing extra understanding of the processes being modeled (Burrough et al. 2005).

Batty (2005) describes a spatial process as a mapping through space and time using equation [1] shown as:

$$p^{l}_{it+1} \leftarrow f[p^{k}_{u}] \qquad [1]$$

where: p = value or attribute
k = entity, object or agent
i = location
t+1 = time step
l = position of object-agent

According to Batty (2005), this is one possible description *of the position of object agent l in location j at time t=1 which is some function of the position l of object k at a previous time period t, from which a trajectory of change at this elemental level can be constructed.* However, Batty (2005) uses this formula to track detailed trajectories of *moving* objects in space and time. Fortunately, this dissertation focuses on forests and trees, which change their characteristics overtime, but do remain stationary. Hence, the challenge here is to develop a new and relevant geographical model that *only* involves temporal dynamics. In other words, this type of model mainly simulates a first order change that is implied by equation [2]:

$$\Delta P_{it} = P_{it+1} - P_{it} \qquad [2]$$

where: P_{it} = variables represented as layers at more than one point in time
t+1 = time step

Here conventional GIS software can do more than appears at first sight. According to Batty (2005), it is possible to build a predictive model that involves combinations of temporal layers related through map algebras that allow complex functions to be implemented. He suggested that this can be accomplished either within the GIS software itself or using separate software, which is then loosely coupled to GIS software for visualization purposes.

According to Burrough et al. (2005), dynamic modeling involves computing the temporal change of the state of an entity in response to information from the inputs and the processes that act in the system being modeled. In a dynamic modeling program, a temporal change is represented by discrete time steps, in accordance with equation [3], which represents changes in each time step:

$$z_{t+1} = f(z_t, i_t) \qquad \text{for each } t \qquad [3]$$

where: z = change in state of entity/object/grid cell
t = time step
t+1 = next time step
f = function of the process
i = inputs or driving forces

Another important aspect of temporal and spatial modeling is how these components are resolved and at which scales they are measured and how and where the objects that define dynamic processes are located (Batty 2005). The term "resolution" for most people means spatial resolution, or the size of the smallest feature represented on a map or in a database (Goodchild 2005). However, in dynamic models temporal resolution is also important, because it defines the length of a model's time step. A dynamic model consists of a sequence of discrete time steps, each representing a set time interval. The model then determines the state of the system being modeled at the end of each time step, based on the input provided at the beginning of that time step. Just as it is the case with spatial resolution, the temporal resolution needs to be appropriate for the system being modeled (Goodchild 2005). The finer the resolution, the better the relationship between the model and the real world. However, one still needs to keep in mind the computing power of the hardware and software available and find a happy medium. The real world and the world created in the computer will never be identical, but it would be unnecessary to model a forest ecosystem on a daily basis, whereas a time step of 50 years may be too extreme in the other direction, depending of what is being modeled. In terms of selecting spatial resolution, bottom-up processes have been found to be more effective in explaining geographic change than top-down, because the bottom-up approach captures the complexity of systems better and enables phenomena to emerge higher and at more aggregate scales (Batty 2005).

A dynamic GIS model would conceivably consists of a number of different interacting submodels, each modeling a different process, with the set of submodeled defined so as to cover a mapped region; this allows several submodels to be active simultaneously for the geographic location (Miller et al. 2005). These authors also described five levels of dynamic GIS models: Simple Evolution Models; Local Dynamics Models; Coupled Dynamics of Single System Models; Coupled Dynamics, Multiple Systems Submodels; Dynamically Changing Model Structure. The simple evolution models generally project the evolution of a particular type of attribute over time, with no interaction with other attributes of neighbors. An example would be a forest stand height, which is an attribute value with a specific location in a table – basically a growth rate model. A local dynamic model specifies how multiple properties of a feature or row in a table interact with one another and evolve overtime. However, neighbor cells do not interact. In terms of a tree growth model, the interacting features determining the growth rate, might be soil type, elevation and aspect. Coupled dynamic, single-system models are basically local dynamic models that are allowed to interact with their neighbor cells/grids. However, all local models need to be of the same type and have the same variables. Coupled dynamic, multiple models take the process one step further, and allow single systems of different types to interact with each other. Here the user needs to specify the interactions between the models, but single models can operate in the same geographic location (biological and physical models, for example). The most complex dynamic modeling approach is the dynamically changing model structure, which not only allows the properties of the models elements of change, but the model structure itself can change over time (i.e. flood boundaries change as spatial features change over time.)

One example of a spatial-temporal data model that has been developed for use in ArcGIS is Arc Hydro (Maidment 2002). This tabular time series model works well for describing time-varying information on discrete features (Maidment et al. 2005). In fact, data tables containing up to five million records have been constructed. Because database performance diminishes with increase in data table size, it is recommended to keep personal ArcGIS databases to no more than 100,000 records. For larger databases, time series tables should be split and stored in a fully relational database such as AQL/Server or Oracle using enterprise ArcGIS (Maidment et al. 2005).

2.5 SPATIAL DISTRIBUTION, LANDSCAPE MODELING, AND ADAPTIVE MANAGMENT

Any model that describes the variation of one or more phenomena over the Earth's surface (or that of any other planet for that matter) is a spatial model (Goodchild 2005). GIS is a particularly good platform for spatial modeling, because its input depicts spatial variation. If modeling goals include describing past behavior or predicting of future outcomes of management policies or actions on ecosystems, spatial or geographic modeling is essential (Risser et al. 1984, Costanza et al. 1990, Sklar and Constanza 1991, Constanza and Voinov 2003, Maxwell and Voinov 2005).

Modeling ecosystems on a landscape scale is a complex process, which can be simplified using state-of-the-art modeling software, such as ArcGIS ModelBuilder, (see section 2.3). This graphical, icon-based diagrammatical module, allows new users to recognize the major interactions at a glance (Miller et al. 2005). This is important, because decision makers and stake holders are unlikely to trust a model that they do not understand (Maxwell and Voinov 2005). The more general objectives of landscape modeling are to predict changes in land cover patterns across large geographic regions (tens to hundreds of square kilometers) over long time scales (tens to hundreds of years) as a result of various site-specific management alternatives and natural changes (Costanza et al. 1990). Probably the best-known example of a forest ecosystem model on a landscape scale is the Forest Ecosystem Management Assessment Team's Management Plan for Old-Growth Ecosystems within the range of the Northern Spotted Owl in the Pacific Northwest United States (Vogt et al. 1997). While FEMAT (1993) suggested four spatial scales, namely regional, physiographic province, watershed and site, other authors disagree. Körner (1993), Levin (1993), and Reynolds et al. (1993) have suggested that a primary consideration of ecosystem management should be the identification of scale at which manageable ecological processes occur. Because units of forest ecosystem scale do not have functional boundaries, physical boundaries can be delineated based on management objectives (Vogt et al. 1997).

The southwestern ponderosa pine forest ecosystem, which is the focus of this dissertation, also has shifting boundaries, but has been relatively stable for the past several hundred years (Swetnam 1990, Swetnam and Baisan1996). Recent extremes in climatic weather and fire patterns, especially in the southwestern forest ecosystems can potentially lead to regime shifts that may be irreversible (Folke et al. 2004). Hence, it is more important than ever before to have models that land managers and decision-makers can use as tools to make management decisions on a landscape scale. In addition managers are faced with greater uncertainty about how ecosystems will respond to increasing human use (Steffen et al. 2004) and disturbances (Jackson et al. 2001, Paine et al. 1998). Here a spatio-temporal MODM landscape model becomes a useful tool that can synthesize the challenges land managers and decision-makers face and allow them to address these challenges in a framework of adaptive management.

In adaptive management, land managers acknowledge that the ecosystem they manage will be different in the future and are willing to deal with changing circumstances (Thomas 2006). However, it is hard to determine whether these changing circumstances and ecosystem differences are legitimate or whether land managers are just setting up a "laissez-faire" project (Sehlke 2006). Hence, it can be problematic to engage decision makers and stake holders in the adaptive management decision-making process, given that the future is abounding with uncertainty. It is essential to establish concepts and criteria for implementing scientifically credible and defensible management alternatives that can get widespread acceptance from decision makers and stakeholders. Yet in order to achieve management goals and objectives, it is evitable that future adjustments in the course of management will be required (Thomas 2006). A tool, which is comprised of several modeling software modules, such as the model proposed in this study, can be used for prediction and planning purposes. Managers, even under the adaptive management concept, will only have to propose hypotheses in which proposed management actions are expected to produce the anticipated results with anticipated ecological concept. This is where monitoring, or the assessment of the results of these proposed treatments, and subsequent adjustments in the plans under the concept of adaptive management come in to play (Thomas 2006). This is an essential part of adaptive management. There are numerous recent examples of where these two concepts – adaptive management and monitoring – have been implemented successful on a landscape scale, such as The Lake Tahoe Watershed (Murphy and Knopp 2000), The Sacramento-San Joaquin Bay Delta (NRC 2004), The Florida Everglades (NRC 2004), The Grand Canyon of the Colorado River (NRC 2004) and the Upper Mississippi River (NRC 2004.)

2.6 MULTI-OBJECTIVE DECISION MAKING (MODM)

Multi-Criteria Decision Making (MCDM) has its origin in the field of Operations Research (Zeleny 1982), which, in turn, was started by the military during the Second World War to optimize submarine warfare in the Atlantic Ocean (Morse 1986). Since then, MCDM has been developing into a discipline with its own concepts, approaches and methods to aid decision makers (DMs) to identify, describe, evaluate, sometimes sort, rank, and select or reject alternatives, based on evaluation processes that involve several criteria (Colson and De Bruyn 1989; Tecle and Duckstein 1993). MCDM basically is a technique that describes the performance levels of alternatives in achieving desired management goals. This description is made in the form of constructing a matrix of criteria versus alternatives. The technique can be divided into two broad classes (Zimmermann 1996, Phoa and Minowa 2005): (1) Multi-attribute decision making, which evaluates a finite feasible set of alternatives and selects the best one based on the scores of a set of attributes; and (2) Multi-objective decision making, which selects the best alternative on the basis of its performance levels in achieving on a set of conflicting objectives. Both processes can be used by a single DM or a group of DMs (Phoa and Minowa 2005).

In 1982, Zeleny wrote that with constantly improving computer technology, scientific progress and conceptual advancement in integrated decision-making, MCDM was shifting from simpler to more complex and less certain decision situations. This indicates that the field, though well developed, was still young and its full potential had not been fully exploited yet. According to Triantaphyllou (2000), MCDM has been one of the fastest growing problem-solving methods over the past two decades. Hence, more than twenty years after Zeleny's prediction the potential has not been fully reached, despite the large body of research and publications on multi-criterion decision-making. One of the reasons MCDM techniques have not been fully exploited is that managers are still unfamiliar or feel uncomfortable with its tools and methods (Pomerol and Bara-Romero 2000). This is especially true in business where most corporations are preoccupied with single objective (or project) maximization. The problem in ecosystem management, on the other hand, is mostly due to unfamiliarity with or the lack of expertise on the approach. The low number of MCDM techniques applied so far, has primarily been to determine optimal timber harvesting methods (Duerr et al. 1979; Garcia 1990). While MCDM techniques have been primarily assuming homogeneity within a study area and were basically aspatial (i.e. Poff 2002, Phoa and Minowa 2005), many

MCDM problems in reality vary across space (Tkach and Simonovic 1997, Malczewski 1999a).

Even though MCDM integration into GIS received considerable attention among urban planners (Carver 1991, Malczewski 1996) and in land allocation problems (Jansen and Rietveld 1990, Eastman et al. 1995, Yeh and Li 1998), relatively few studies have employed MCDM with GIS techniques in forest management planning (Phoa and Minowa 2005). In the past few years, GIS have been used to find solutions to natural-resource management and planning problems, such as the Patuxent Landscape Model (PLM 1995, Costanza et al. 2002, Voinov et al. 2003), the Everglades Lanscape Model (ELM 1997) and the Land Use Evolution and Impact Assessment Model (LEAM 1999). This has opened the door for GIS-based multi-criteria decision making (Ratsiatou and Stefanakis 2001), leading to the development of spatial decision support systems that incorporate forest planning models into a GIS format (Næsset 1997).

Malczewski (1999b) suggests that visualization of spatial MCDM analysis outcomes are critical leading to attempts to integrate MCDM tools with GIS. This has led to several prototypes in the past decade (Jansen and Rietveld 1990, Carver 1991, Farber et al. 1995, Jankowski 1995, Lotov et al. 1997, Tkach and Simonovic 1997, Wu 1998, Jiang and Eastman 2000).

As with simulation software, there are three basic ways of integrating MCDM into GIS software: (1) The first one involves incorporating MCDM tools within the GIS software (Jiang and Eastman 2000), (2) the second one imbeds GIS techniques and tools within the MCDM software (Fisher et al. 1996), and (3) the third integrates both at the operating system level (Jankowski et al. 1997). According to Morris and Jankowski

(2000) the main problem with MCDM-GIS integration is that the approach used to assign weights to the criteria is either somewhat arbitrary or assumes that criteria are strictly Boolean.

One MCDM technique that has been successfully applied in a GIS framework is Compromise Programming (Rogowski and Engman 1996, Tkach and Simonovic 1997, Bukenya 2000, Simonovic 2002, Thinh and Hedel 2004). However, none of these examples involve dynamic models and primarily focus on either cleaning up remotely sensed data or determining land suitability for various natural resource management problems. That is because this area of modeling involves methods that are being used to optimize some set of goals or objectives, in terms of planning, design, policy and management. Commonly planning and management processes are regarded as so complex that it is thought to be not possible to build a spatial model optimized in a fashion that meets the diversity and complexity of political aspirations of decision makers (Batty 2005). Some dynamic decision support tools that have been applied on landscape scales include the Patuxent Landscape Model (PLM 1995, Costanza et al. 2002, Voinov et al. 2003), the Everglades Lanscape Model (ELM 1997) and the Land Use Evolution and Impact Assessment Model (LEAM 1999). These models have allowed decision makers, stakeholders and concerned citizens to visualize and test impacts of management actions on urban, environmental, social and economic systems (Maxwell and Voinov 2005). However, none of these models use the classical MCDM/MODM techniques as defined above.

The closest true spatial-temporal MODM model found in the literature is still conceptual. According to Maidment et al. (2005) three basic questions have to be addressed when setting up a spatial-temporal model: (1) What is the spatial domain of the model and how will that domain be subdivided into analysis units? (2) What is the time horizon for the model and into what intervals will this horizon be subdivided for modeling purposes? (3) What variables will the model determine? These considerations can be illustrated in a data cube form as shown in Figure 1.

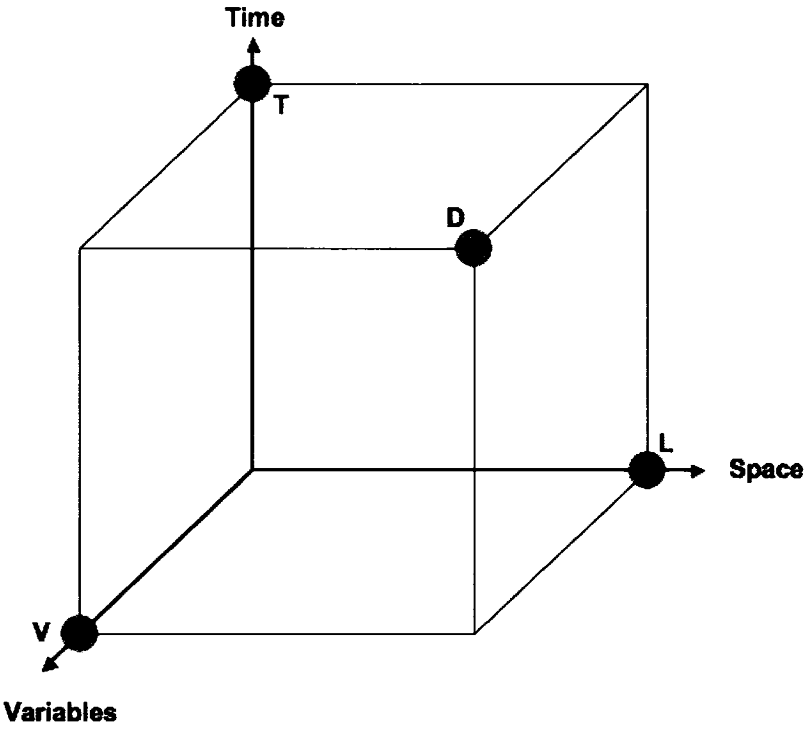

Figure 1: Data for a variable measured at a particular point in space and time. A data value D is a function of what feature it describes, what time it represents and what variable it is: D(L,T,V) (from Maidment 2002). This conceptual data cube is the basis for the tabular times series model used in the Arc Hydro data model.

Even though advances in computer technology have made complex simulation models feasible from a computational standpoint, the difficulty of obtaining a model output that is satisfactory increases sharply with its complexity (Costanza et al. 2002). They also suggest that multi-objective calibration of spatially explicit models, because in many cases only a combination of different objective functions can express the calibration criteria correctly.

2.7 CHAPTER SUMMARY

The ponderosa pine forest ecosystem in the southwestern United States presents land managers and decision makers with many conflicting management objectives. Foresters are often asked to achieve specific societal objectives within ecological and economic constraints. Because these objectives, such as aesthetic quality, biomass, timber, forage for livestock or wildlife, the quantity and quality of water, reduction of fire and flood hazards, recreational use, extraction of mineral resources, wildlife habitat, promotion of healthy interaction between components, diseases and pathogens or invasive exotic plant species control, etc., require conflicting management actions, a multi-objective decision making method that can be applied dynamically and on a landscape scale can be helpful in the decision making process. Hence, using existing spatial and dynamic computer programs such as FVS and GIS, as described in this chapter, can be combined with a MODM model using multiple forest management objectives to come up with spatio-temporal solutions for a forest ecosystem management problem on a landscape scale.

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CHAPTER 3 - SPATIO-TEMPORAL MULTI-OBJECTIVE DECISION MAKING IN FOREST MANAGEMENT

***Abstract*:** The Multi-Objective Decision Making (MODM) process in forest management is evaluated on spatial and temporal scales. A conceptual model intended for forest managers and decision-makers (DMs) is assembled as a set of one MODM technique and two modeling programs – one spatial and one dynamic. Compromise Programming (CP) is the MODM technique utilized in this ecosystems modeling effort. An individual-tree growth model (Forest Vegetation Simulator) is used to describe vegetation changes with time, while a Geographic Information System (ArcGIS) is used to display the spatial aspect of the model and allows for spatial statistical analysis.

The management of forest ecosystems involves multiple interests and stakeholders with different and often conflicting expectations and management objectives. Today's ecosystems must accommodate commercial as well as non-commercial objectives, both quantitative and qualitative, and respond to social, political, economic as well as cultural changes. Given the complexity and number of variables involved in the management of ecosystems and considering the forest planning software available today, it makes sense to model forest system management in a spatio-temporal MODM framework. This paper shows how forest managers can identify numerous feasible forest management alternatives in terms of reduction of the vegetation density, as well as to what extent the identified alternatives achieve the selected management objectives over time and space.

3.1 INTRODUCTION

The ponderosa pine forest ecosystem in the southwestern United States presents land managers and decision makers with many conflicting management objectives of specific societal, ecological, environmental and economic values. These objectives include improving desirable objectives, such as aesthetic quality, timber yield, forage for livestock and/or wildlife, recreational use, quantity and quality of water, and reducing undesirable objectives, such as fire and flood hazards, invasive exotic plant species, etc. Often these objectives are conflicting and non-commensurable, which tend to change with time and space. A Multi-Objective Decision Making (MODM) method combined with spatial and dynamic computer programs is used to solve the problem in a spatio-temporal management decision-making framework. The specific subject of this study is the ponderosa pine forest in northern Arizona, which land managers and scientists consider to be above its historical stand density and prone to catastrophic forest fires (Covington et al. 1997, USFS 2006). The problem is further complicated by the number of stakeholders and interested parties with strong feelings and mostly conflicting objectives in the way the forest should be managed (Tecle et al. 1995). This paper presents a stepwise methodology to solve a particular forest ecosystem management problem in a multiobjective and time variant framework across a landscape.

3.2 METHODOLOGY

The modeling approach in this study consists of developing a set of response functions and use of one MODM technique in a spatio-temporal framework. A *Response Function* is a mathematical expression of a management objective or forest ecosystem component response to certain management action(s). In this study the management objectives are linked to varying levels of forest stand densities and solved using a MODM technique, Compromise Programming (CP), a forest growth and yield model, Forest Vegetation Simulator (FVS) and a Geographic Information System model (ArcGIS). FVS is an individual-tree growth model used by forest managers in developing their land management plans. ArcGIS is a Geographic Information System used by land managers and analysts for creating, storing, analyzing and managing spatial data and associated attributes. GIS is used here as the spatial projection component of the modeling effort which assigns CP analysis results to polygons. These three components are combined to achieve one goal: to solve a multi-objective forest management problem in a dynamic and spatially varied framework to reflect a real world situation.

3.2.1 Procedural Steps

Evaluation of forest ecosystem management in a spatio-temporal MODM framework requires a series of steps. The following steps summarize the MODM formulation and analysis procedures, and the forest growth and spatial display mechanisms used to evaluate the achievement levels of various forest management alternatives and select the most preferred one on the basis of attaining the desired objectives:

1. Identify forest ecosystem management objectives that reflect the needs and aspirations of stakeholders.
2. Describe the forest management objectives in the form of specifications, criteria and criterion scales as shown in Table 3-1.

3. Identify an appropriate management decision variable(s), the levels of which can be evaluated to achieve the desired management objectives
4. Built response functions that relate objectives to the management decision variable (see Table 3-2).
5. Provide opportunity for management team, stakeholders, and/or decision makers to express their preferences structure on the management objectives by assigning weights to individual objectives.
6. Evaluate the objective response functions developed in step 4 and the generated weights in step 5 in an integrated manner using CP.
7. Perform model sensitivity analysis to weights and *p*-values.
8. Run a FVS simulation based on:
    a. the most appropriate management decision variable level determined using CP
    b. the thinning/burning prescription selected by the management team
    c. the individual forest stands in the project area for which the management team is responsible, and
    d. the time step and scale selected by the management team
9. Import the FVS simulation output into ArcGIS.
10. Use ArcGIS Modelbuilder, to display the FVS simulation results translated into achievement levels, on the basis of the preferred management decision variable.
11. Analyze the performance of the selected management decision variable level in achieving the desired objectives at each time step.

12. Present the solutions to the Decision Makers (DMs). If the solution is not acceptable, the procedure may be repeated starting at either:
    a. Step 2 by gathering more information and if necessary introducing new objectives and/or response functions (Step 4); or
    b. Step 5 by selecting a different weighting scheme for the individual objectives; or
    c. Step 8 by using a different decision variable level, prescription and/or time step/scale.

Table 3-1: Objective Categories, Specifications, Criteria and Criterion Scales of the multi-objective management plan for a ponderosa pine forest ecosystem

Objective Categories	**Specifications**	**Criteria**	**Criterion Scale**
Maximize *Social Benefits*	Aesthetic Quality	Scenic Beauty Index	Ordinal
	Cultural Resources	Willingness-to-pay	US$/BA
	Recreational Use	Willingness-to-pay	US$/BA
Minimize *Insects & Diseases*	Roundheaded Pine Beetle Attacks	Beetle Attacked Trees	% of BA killed
	Bark Beetle	Hazard Rating	Composite Stand Hazard Values
	Dwarf Mistletoe Infection	Dwarf Mistletoe Rating	10 yr Infestation Rate
Minimize *Exotics*	Invasive Plant Reduction	Individual Exotic Plants	Plants/Ha
Maximize *Forage*	Herbage Production	Amount of Herbage	t/Ha
Maximize *Timber*	Timber Growth	Timber Yield	m^3/Ha
Minimize *Costs*	Costs	Cost of Tree Removal	US$/Ha
Minimize *Fire Hazard &Effects*	Forest Fire	Crown Fuel Load	t/Ha
		Heat Intensity	kJ/m^2
		Crown Fire	% Crown Burned
Achieve Desirable *Hydrological Condition*	Maximize Water Quality	Sediment Yield	t/ha/yr
	Maximize Water Yield	Streamflow	m^3/sec
	Minimize Flood Hazard	Peak Flow	m^3/km^2
Optimize *Wildlife Habitat*	Non-Game Species	Abert Squirrel	Ordinal
	Threatened/Endangered Species	Mexican Spotted Owl	Ordinal
	Game Species	Mule Deer	Ordinal
	Forest Service Sensitive Species	Northern Goshawk	Ordinal

Table 3-2: Summary of Response Functions

Objectives	Based on	Mathematical formulations of management objectives	r^2 values	Eq. #
Social Concerns >Aesthetic Value >Cultural Resources >Recreation	Brown et al. (1974); Tecle et al. (1998) Loomis (1996) Loomis (1996)	Z_1 = 1.144-0.001974(x/0.2296)+0.004718(x/0.2296)^2-0.000004356(x/0.2296)^3+0.000000001059(x/0.2296)^4 Z_2 = -59.334+10.221x-0.206x^2 Z_3 = -16.03+2.706x-0.054x^2 Where Z_1 = Scenic Beauty Estimator Index (SBE) Z_2 = Willingness-to-pay for forest preservation at given ba/ha Z_3 = Willingness-to-pay for recreational experience in given basal area/ha x = Tree basal area m^2/ha	N/A N/A N/A	1 2 3
Insects and Diseases >Roundheaded Pine Beetle >*Dendroctonus* Bark Beetle >Dwarf Mistletoe Intensification Rate	Negron et al. (2000) McMillain (2006) Geils and Mathiasen (1990)	Z_4 = 0.453+0.044x-0.000025x^2-0.0000021x^3 Z_5 = 1+0.218x+0.00000000000000231x^2-0.000000000000000033x^3 Z_6 = 0.697+0.013x-0.0000007x^2 Where Z_4 = Percent ponderosa pine basal area killed from roundheaded pine beetle Z_5 = Composite Stand Hazard Values from bark beetle infestation Z_6 = 10-Year Dwarf Mistletoe Infestation Rate/ha x = Tree basal area m^2/ha	0.88 1 N/A	4 5 6
Min. Exotic Species	USFS Data, Coconino NF (1999)	Z_7 = 36.57-2.097x+0.053x^2-0.0005x^3 Where Z_7 = Number of Scotch thistles observations/ha x = Tree basal area m^2/ha	0.55	7
Max. Herbage Production	Covington & Fox (1991) Tecle et al. (1998)	Z_8 = {(45+24a/25.4+55d)(exp(-0.0289(x/0.23))}*1.1208 Where Z_8 = herbage production a = annual precipitation (= 762 mm average for study area) d = depth of soil to impedance layer (cm) (= 30 cm average for study area) x = Tree basal area m^2/ha	N/A	8
Max. Timber Production	Ronco et al. (1985), Tecle et al. (1998)	Z_9 = 17.06(x/0.2296)-0.03369(x/0.2296)^2*0.06997 Where Z_9 = merchantable timber growth volume in m3/ha x = Tree basal area m^2/ha	N/A	9
Min. Operational Costs	Turner and Larson (1974)	Z_{10} = 1486.35-33x Where Z_{10} = Cost of Thinning to desired basal area expressed in 2000 US\$ x = Tree basal area m^2/ha	N/A	10

Min. Fire Hazard & Effects				
>Fire Hazard	Fulé et al. (2001a, 2001b)	$Z_{11} = -0.37+0.34x$	0.96	11
>Heat Generated		$Z_{12} = 1.763+8.54x-0.398x^2+0.008x^3$	0.75	12
>Size of Fire		$Z_{13} = 5.818+0.212x+0.041x^2$	0.52	13
		Where Z_{11} = Crown Fuel Load (t/ha) Z_{12} = Heat Generated (kJ/m^2) Z_{13} = Percent of Crown Burned (%) x = Tree basal area m^2/ha		
Hydrological Concerns				
>Water Quality	Brown et al. (1974)	$Z_{14} = 14.82-0.34x$	N/A	14
>Water Yield	Rogers et al. (1984); Tecle et al. (1998)	$Z_{15} = 1.19\{-5.72+0.83Pw/25.4+42r-0.24r(Pw/25.4)^{0.92}-0.007Pw^2(1-\exp[-(x/0.23)/45)]^3\}-0.47$	N/A	15
>Flood hazard	Brown et al. (1974); Ffolliott and Thorud (1975); USDA Forest Service (1977); Tecle (1991), Tecle et al. (1998)	$Z_{16} = 76.27-1.04x$	N/A	16
		Where Z_{14} = Sediment yield in t/ha Z_{15} = annual streamflow in cfs Z_{16} = m^2/km^2 of water flow Pw = winter (1 Oct. –30 April) precipitation (= 610 mm average for study area) R = insolation index (= 1.9 INI for study area) x = Tree basal area m^2/ha		
Wildlife Habitat Condition				
>Abert Squirrel	Patton (1984); McTague (1991) Tecle et al. (1998)	$Z_{17} = 0.857+0.02713x+0.0003027x^2$	N/A	17
>Mexican Spotted Owl	Ganey (1988)	$Z_{18} = 0.056-0.033x+0.0044x^2-0.00005x^3$	0.47	18
>Mule Deer	Wallmo and Schoen (1981); Leckenby et al. (1982); Severson and Medina (1983)	$Z_{19} = 1.659+0.386x-0.017x^2+0.0002x^3$	0.74	19
>Northern Goshawk	Reynolds et al. (1992), Block et al. (1994)	$Z_{20} = 0.459-0.295x+0.025x^2-0.0004x^3$	0.86	20
		Where Z_{17} =Abert Squirrel Habitat Index Z_{18} = Mexican Spotted Owl Habitat Index Z_{19} = Mule Deer Habitat Index Z_{20} = Northern Goshawk Habitat Index x = Tree basal area m^2/ha		

N/A: r^2 value is not available because the original response function has been developed by respective authors and value was not given.

k = 1,…K, where K = 9

Each k has 1 - 4 specific objectives, represented by I.

When $I \geq 2$ a first stage evaluation is performed using the CP algorythm given in equation 21, to arrive at a joint response function value for each objective category.

When I = 1, no first stage CP evaluation is performed on that objective category; instead each objective category's values are determined for use in the second stage CP evaluation.

3.2.2 Compromise Programming

The multi-objective analysis approach used in this study is Compromise Programming (CP). CP employs the concept of distance to analyze multiple-objective problems. This distance is not limited to the geometric sense of distance between two points; it is rather used as a proxy to measure human preferences. CP selects a preferred solution from a non-dominated and feasible set, on the basis of the solution's closeness to an infeasible ideal point (Zeleny 1973). A non-dominated solution in a MODM problem is one that cannot produce any improvement in any one of the objectives without making at least one other objective worse (Tecle et al. 1988, Tecle and Duckstein 1994), while an ideal point represents the joint location of the maximum values of all the objectives optimized separately. Therefore, arriving at a compromise solution can be viewed as minimizing a DM's regret for not obtaining the ideal solution. The general formulation of a CP technique is expressed as follows:

$$\min \{l_\mathrm{p} = [\sum_{i=1}^{I} W_\mathrm{i}^\mathrm{p} (Z_i^* - Z_{ij})^\mathrm{p}]^{1/\mathrm{p}}\}, j = 1, \ldots, J \qquad [21]$$

Here l_p is the distance metric, for any p in which $0 < p < \infty$. It is the measure of a solution's closeness to the ideal point Z^*, which is the set of all the maximum values of all objective functions. Z_{ij} is the value of objective i under a specific discrete value of decision variable j. I is the number of objectives within categories and may range from one to four. J is the number of discrete decision variable values. Z_i^* is the maximum value for objective i and it is determined using equation [22].

$$f_i^* = df_i / dx \qquad [22]$$

where f_i is a response function (in equations [1] – [20]) and x is the decision variable in f_i.

To demonstrate the procedure, the Z_i^*, the best value and Z_i^{**}, the worst value for the mule deer habitat response function [Equation 19] is determined in the following manner:

$$f(x) = 1.659+0.386x-0.017x^2+0.0002x^3 \qquad [19]$$

$$f'(x) = 0 \text{ ; for } 6 \le x \le 45$$

$$0.386 - 0.034x + 0.0006x^2 = 0$$

$$x = (0.034 \pm \sqrt{}((-0.034)^2 - 4(0.0006)(0.0386)) / 2(0.0006)$$

The solutions are x = 15.905 for the best value and x = 40.429 for the worst value of the response function, and they are used for the Z_{19}^* and Z_{19}^{**} values, respectively.

To avoid scale effects and to make all objective function values commensurable, the objective functions are normalized by dividing the right hand side by the expression $Z_i^* - Z_i^{**}$, where Z_i^{**} is the worst value of objective i, which is also determined in equation [22].

The normalized objective functions are expressed in the following manner:

$$Z_{ij} = (Z_{ij} - Z_i^{**}) / (Z_i^* - Z_i^{**}),\ i = 1,\ldots, I \text{ and } j = 1,\ldots, J \qquad [23]$$

where the Z_{ij} on the left hand side of the equation represents the normalized elements of the original pay-off matrix Z_{ij} on the right hand side of the equation. This normalization process guarantees the Z_{ij} on the left hand side of the equation to have values between 0 and 1.

The weight W_i in equation [21] signifies the importance of objective i relative to the other objectives. The p is the metric parameter. Different values of p represent different aspects of a compromise programming algorithm. For $p = 1$, all deviations from Z_i^* are directly proportional to their magnitude. For $2 \leq p < \infty$, the largest deviation has the greatest influence. Varying p from 1 to ∞, allows to move from having a perfect compensation among the objectives (i.e., minimizing the sum of individual regrets) to having no compensation among the objectives in the decision making process (i.e., minimizing the maximum regret). The greater the conflict between different DMs is, the smaller the possible compensation (Zeleny 1974, 1982; Goicoechea et al. 1982; Szidarovszky et al. 1986).

Compromise programming is adapted here to perform a two level trade-off analysis of the ecosystem management problem. In the first level, equation [21] is used to seek a compromise solution within those objective categories that have more than one objective. In the second level, equation [24] is applied to determine the compromise solution of the objective categories:

$$\min \{l_p = [\sum_{k=1}^{K} W_k^{p} (Z_k^* - Z_{kj})^{p}]^{1/p}\}, j = 1,\ldots, J \qquad [24]$$

Z_{kj} is the normalized value of objective category k under decision variable level j, and Z_k^* is the best value for objective category k. K is the number of objective categories and all others are as defined previously. The weight W_k in equation [24] signifies the importance of objective category k in comparison to the other objective categories.

For $p = \infty$, the largest deviation is the only one considered and the problem becomes a min/max problem. As a result equation [24] reduces to equation [25].

$$l_\infty = \max \{W_k (Z_k^* - Z_{kj}), k = 1, \ldots, K \text{ and } j = 1, \ldots, J \qquad [25]$$

where all the variables are as described above.

3.2.3 Response Functions

The management objectives described in this paper represent the interests of various stakeholders. The preferred values for many of these objectives have different stand density requirements, and are in conflict with each other. Under this situation, it is impossible to optimize one objective without adversely affecting another. Hence, a trade off analysis using a MODM technique is required to determine a preferred stand density level that will result in the most satisfactory solution with respect to all management objectives. To use such a technique, the individual management objectives are described in the form of mathematical response functions. The individual forest management objectives, their specifications, criteria and criterion scales used in this study are shown in Table 3-1. Tree basal area (in m^2/ha) is the management variable used to develop and express the different objective functions. In order to be meaningful to managers the decision variable must be susceptible to alteration by management actions. Hence, all response functions in this study are expressed in terms of tree basal area that range from 6 through 45 m^2/ha. The minimum density required for the forest in the study area to qualify as "a forest" under UN guidelines (FAO 2006) is 6 m^2/ha. 45 m^2/ha is the average upper limit of the majority of the data available from which the response functions have been created (Poff 2002).

Figure 3-1 represents the trend curves for the 20 management objectives expressed as response functions in Table 3-2. Each graph in the figure represents a change in management objective function values with varying tree basal area levels expressed in m^2/ha. The management objectives were normalized and brought into the same optimization direction before performing CP analysis.

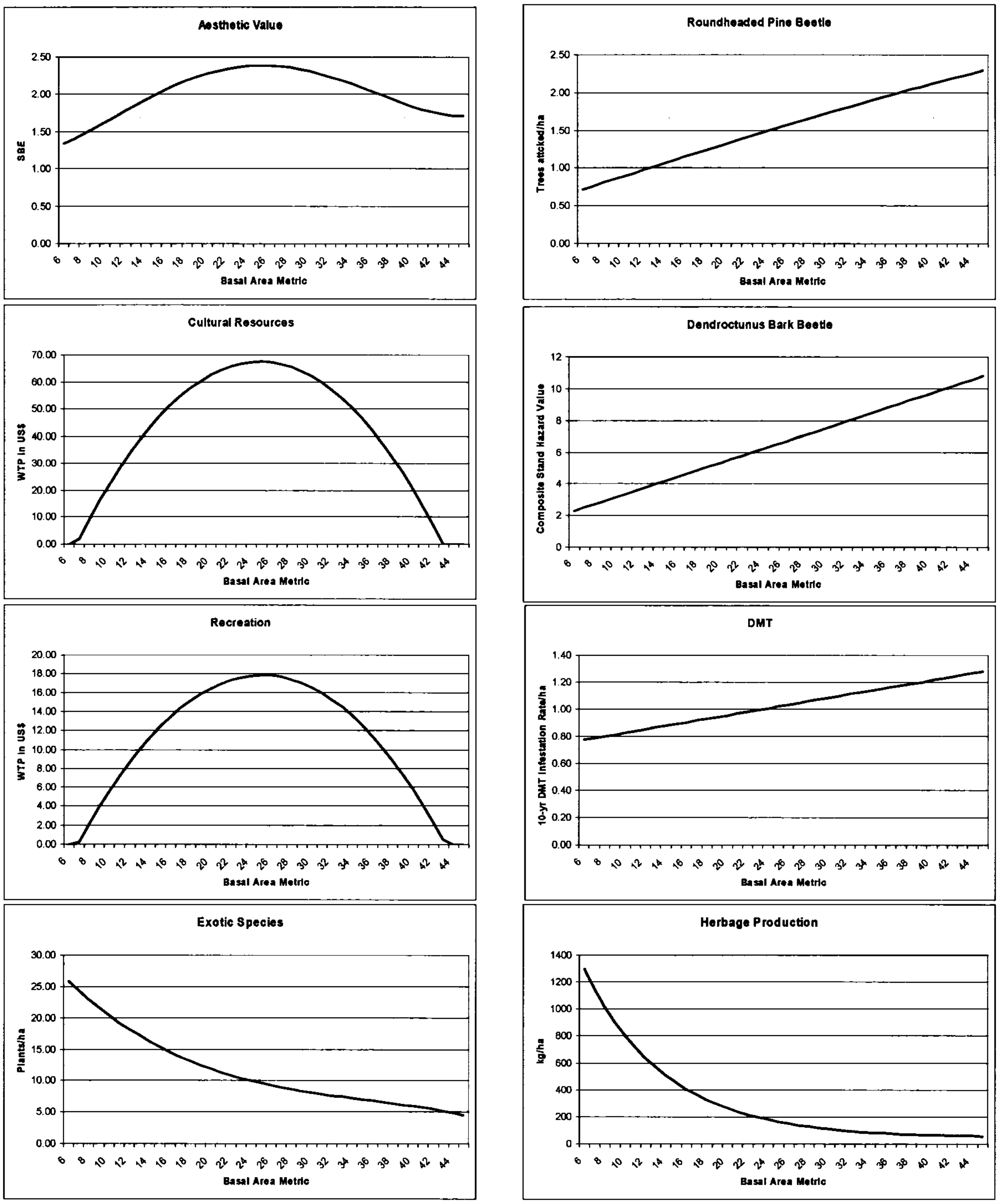

Figure 3-1: Trend curves of forest management objectives versus tree basal area values.

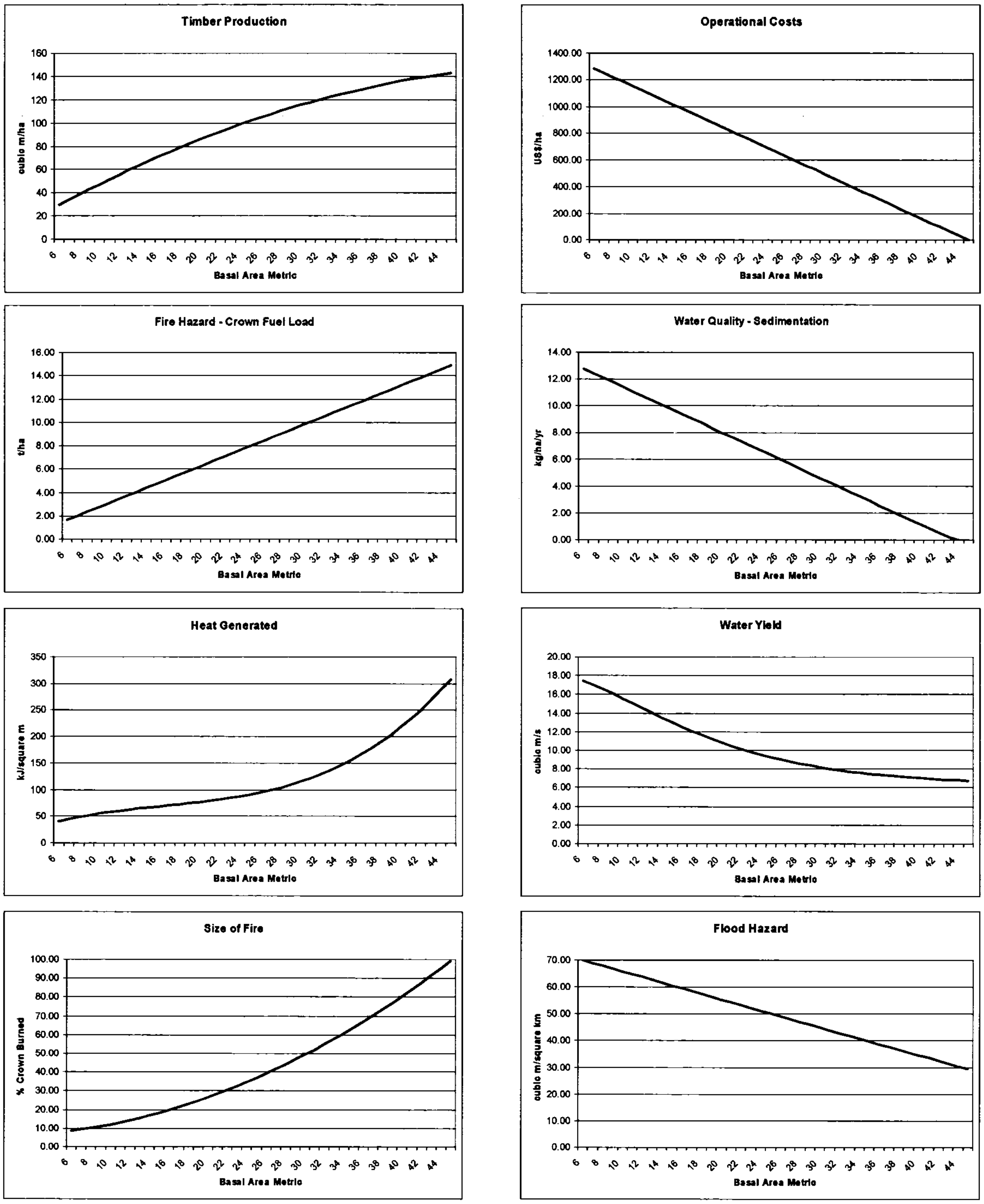

Figure 3-1 cont.: Trend curves of forest management objectives versus tree basal area values.

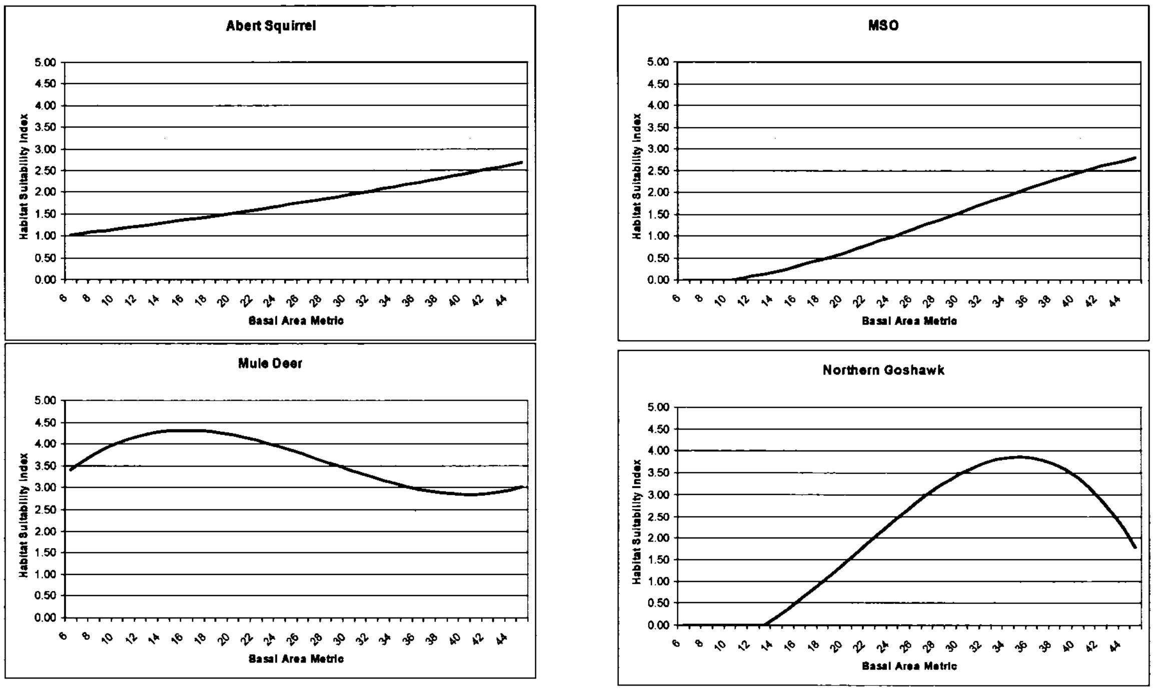

Figure 3-1 cont.: Trend curves of forest management objectives versus tree basal area values.

3.2.4 Temporal Projection using Forest Vegetation Simulator

The dynamic analysis part of the modeling effort is handled using the US Forest Service's Forest Vegetation Simulator (FVS). FVS is a large-scale forest management tool, which is employed to summarize current stand characteristics, predict future stand conditions under various management scenarios (Dixon 2002). Its output can be utilized as an input into forest planning models and other analytical and spatial analysis tools such as the geographic information systems used in this work (GIS) (McMahan et al. 2002). Refer to "Essential FVS: A user's Guide to the Forest Vegetation Simulator" (Dixon 2002) for a more detailed description.

While FVS served as the temporal projection tool in this study, any software that performs similar functions such as Tree And Stand Simulator (TASS) (Mitchell 1975) could be used instead. FVS was chosen because it has been commonly used to simulate growth of southwestern ponderosa pine stands by forest land management agencies in the Southwest (Dixon 2002). FVS computes future forest stand density using measured original stand density. In its most basic form FVS can be expressed as:

$$\Delta T_i = T_{+1} + f(var.),\ i = 1, \ldots, I \qquad [26]$$

Where T_i is the stand density at time step i and *var.* represents a set of variables ranging from physical and spatial characteristics such as slope, aspect and conditions of adjacent stands, to biological conditions such as tree mortality and management variables such as a thinning treatment. The user defines the time scale for the growth simulation in FVS. In this analysis, a common cycle length of 10 years, a starting date of 2007, in which the selected treatment was applied, and an ending year of 2127 were chosen. FVS uses three stand density descriptors, namely basal area per acre, crown competition factor and basal area percentile. However, only tree basal area per acre was used, because it is the decision variable in the entire modeling effort of this study. To compute basal area, FVS simply *sums the product of trees per acre and tree basal area across all tree records.* This is then computed for each stand in the simulation (Dixon 2002).

The FVS post processor used in this study is "Stand Tables and Stock Tables," which allows users to export FVS stand attributes into a spreadsheet. This spreadsheet provides a live basal area column for each stand for each time step. This file is then converted to a *.dbh4* file in Microsoft Excel, so that it can be imported into and used in GIS.

3.2.5 Spatial projection using Geographic Information System (GIS)

ESRI's ArcGIS was used to handle the spatial projection part of the MODM modeling process. The ModelBuilder extension of ArcGIS allows the user to build a model using a diagram that resembles a flowchart (Krivoruchko and Gotway-Crawford 2005, Maidment et al. 2005, Miller et al. 2005). In this feature of ArcGIS, the model consists of a set of spatial processes that convert input data into an output layer. ModelBuilder is not dynamic as of version 9.1, however, it can simulate changes with time by running a model multiple times using different inputs. This was pursued in this study for each time step simulated in FVS. Using the query function in Modelbuilder eleven layers were created for each time-step output given in the FVS table. Here GIS was used to assign the level of closeness to polygons based on their basal area values. This measure of closeness of CP solution to the ideal point serves as a surrogate for the achievement levels of the management problem. Each layer represents a group of forest stands with the same *achievement level*. This can be expressed as:

$$L_i^{TS} = \Sigma \, AL_j^{BA} \qquad [27]$$

where L_i^{TS} is the layer created in time step i and AL_j^{BA} are the polygons of achievement level j given their basal area values.

There are a total of thirteen ten-year time steps (from 2007 – 2127) plus pre-existing stand conditions in this simulation. The eleven layers, for each time step, are color coded in accordance to the color key given in Figure 3-6. As illustrated in Figure 3-7, the user can see at a glance which forest stands in the project area have the best possible basal area that can satisfy all management objectives simultaneously. One can also easily see which stands have too high of a stand density and which stands have too little and by how much. In other words, the MODM spatio-temporal output is displayed by the individual stands across the landscape in the project area using a color coded scheme to show the percentage of the achievement level.

3.3 PROBLEM ANALYSIS

To evaluate the different forest management alternatives with respect to their ability to achieve the desired objectives, the 20 objective response functions were categorized into nine objective categories on the basis of their similarity in addressing related issues as shown in Table 3-1. The process involves translating all response functions into the same optimization direction, maximization where the higher the value of a response function, the higher the achievement level becomes.

The application of the compromise programming algorithm in the first level leads to a compromise solution within each objective category that consists of multiple objectives. There were five objectives categories with two or more objective functions evaluated at this level. Equal weights and a p–metric value of 2 were used at this level of analysis to better show the difference between the individual objectives. Figure 3-2 shows the first level CP evaluation results for the nine different objective categories in the form of trend curves.

The second level of CP analysis involves evaluating the nine objective categories. This consists of calculating the level of closeness for each value of the decision variable, and then determining the most preferred forest stand density under three different cases. The first case assumes all objectives to have equal weights or importance; the second case involves assigning varying weights to the different objective categories; and the third case uses extreme weights. The third indicates a situation where a particular DM is primarily interested in one of the management objective categories. In all cases the CP solutions are determined for p-values of 1, 2 and ∞ to show the sensitivity of the CP solution to p-values.

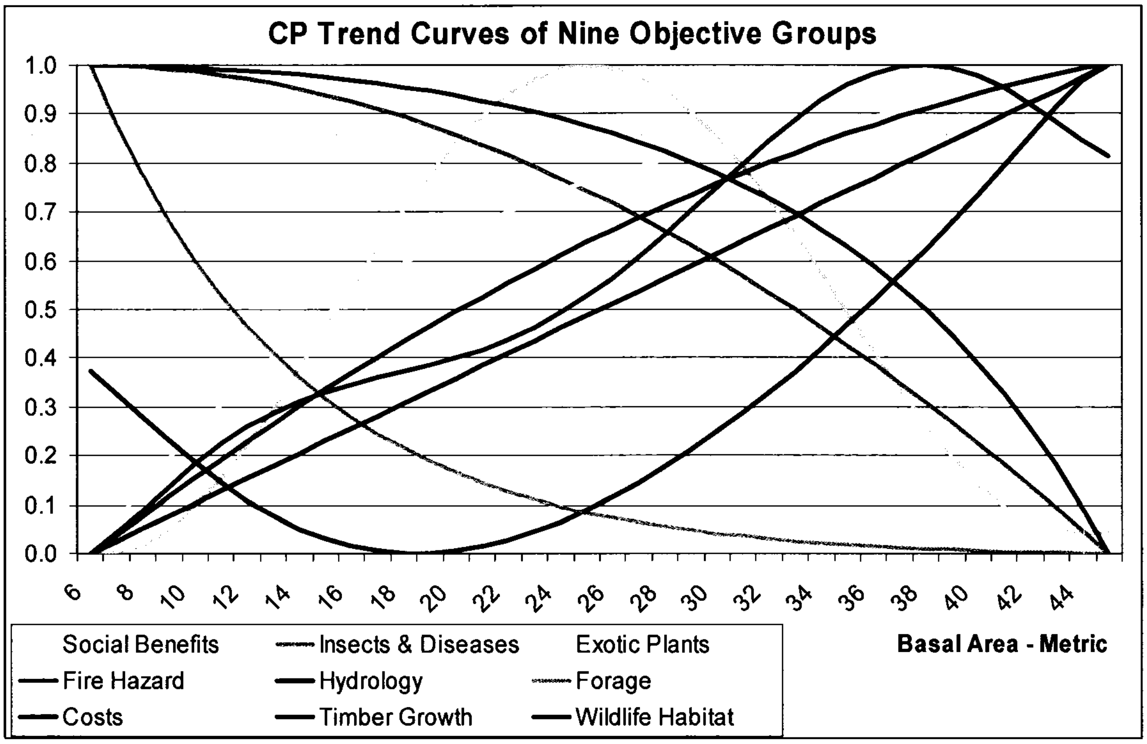

Figure 3-2: Standardized response function curves for the nine objective categories in their individual desired optimization directions.

3.4 MODM RESULTS AND SENSITIVITY ANALYSIS

Three sets of weights (W_i) and three sets of the metric parameter p-values were used to conduct a sensitivity analysis of the modeling effort presented in this paper. The first set of weights consists of equal weights for each of the objective categories. The second set of weights consists of actual weights assigned by a USDA Forest Service Interdisciplinary Team on the Coconino National Forest in Northern Arizona. The weights assigned to each objective category vary from 1-10 where a weight of 1 indicates least important and 10 most important. The third set of weights consists of an extreme case where one objective category (in this case *Optimize Wildlife Habitat*) was given a weight of 10, while each of the eight remaining objective categories received a weight of 1. Figures 3-3, 3-4 and 3-5 display the outcomes of the CP analysis under the three values of p (1, 2 and ∞, respectively) and for the three different sets of weights. The most preferred basal area for each CP weighting scheme and p-values are listed in Table 3-3.

Table 3-3: The most preferred tree basal area with respect to its performance in achieving all 20 management objectives simultaneously under the three different weighting schemes and three values of p.

	P Parameter "p"		
	1	2	∞
Weighting Scheme	Most Preferred Basal Area in m^2/ha	Most Preferred Basal Area in m^2/ha	Most Preferred Basal Area in m^2/ha
Equal	27	25	6, 25, 38, 45
Varying	26	18	6
Extreme	36	38	38

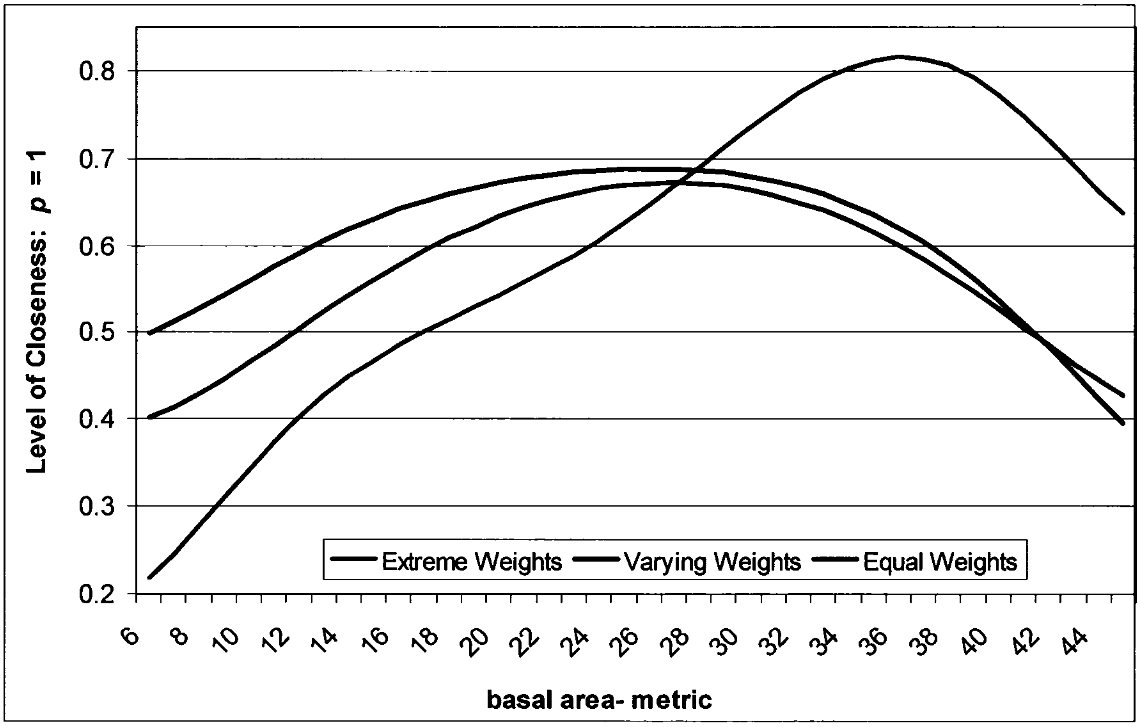

Figure 3-3: The outcomes of CP analysis under the 3 different sets of W_i (equal, varying and extreme) and for $p = 1$.

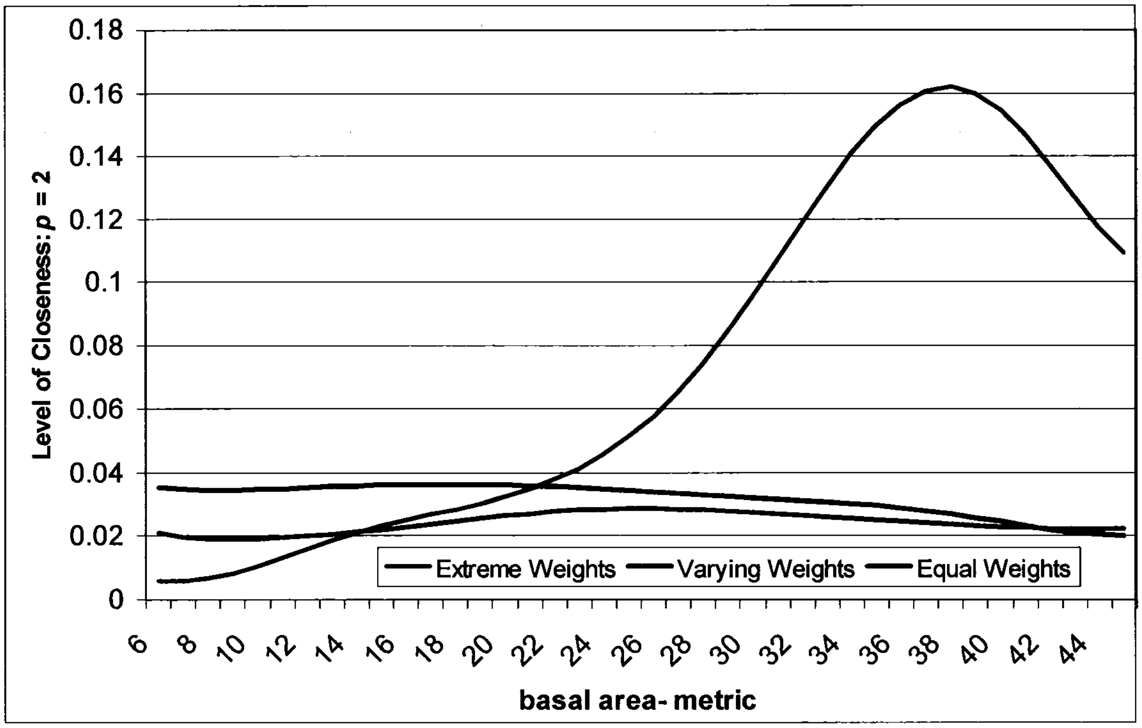

Figure 3-4: The outcomes of CP analysis under the 3 different sets of W_i (equal, varying and extreme) and for $p = 2$.

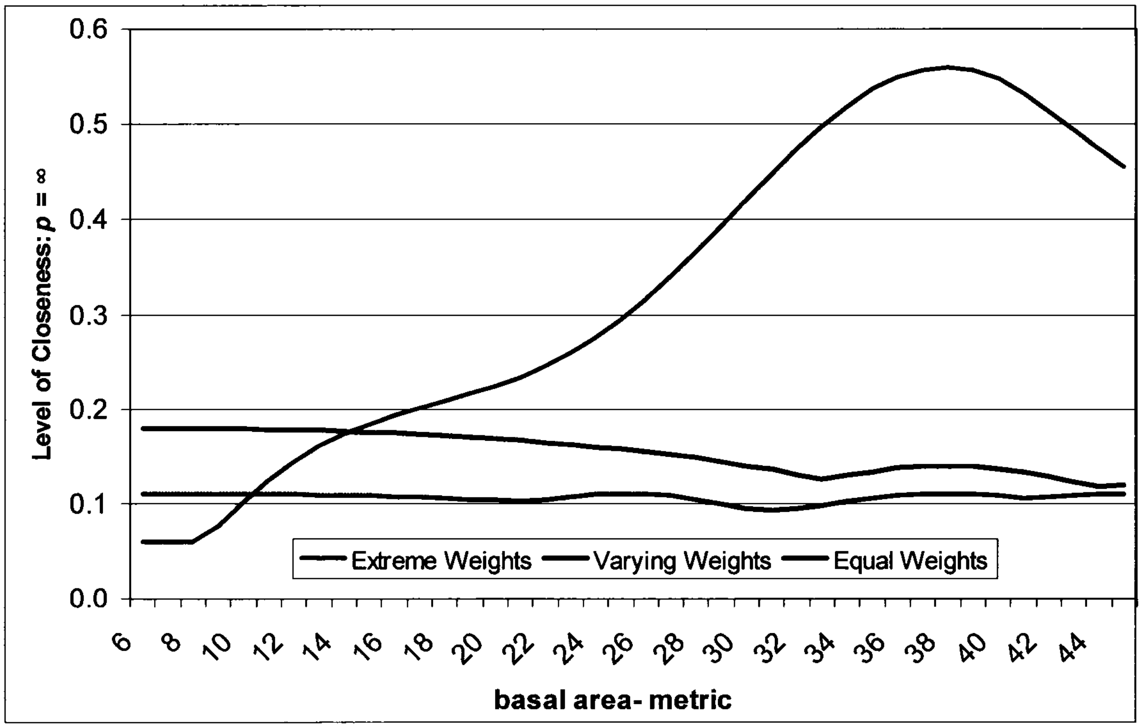

Figure 3-5: The outcomes of CP analysis under the 3 different sets of W_i (equal, varying and extreme) and for $p = \infty$.

In Figures 3-3, 3-4 and 3-5 each weighting scheme (extreme, varying and equal weights) is represented by a trend curve. The decision variable values (expressed in the form of tree basal area in m^2/ha) displayed on the x-axis serve as the vegetation management alternatives. The y-axis is a standardized level of closeness, which ranges from zero to one, where 1 represents the infeasible ideal point. The decision variable values with the highest level of closeness (that is, peaks of the trend curves) represent the most preferred management alternatives with respect to all objectives under the different weighting schemes. Because the level of closeness values are very small, their differences for decision making purposes are better viewed in at least three decimal places otherwise many values may round up to the same number.

The trend curves under the "extreme" weighting scheme in Figures 3-3, 3-4 and 3-5 indicate that the CP analysis results are most robust for a metric parameter value of $p = 1$ and most sensitive for $p = 2$ and ∞. The "extreme" weighting scheme is used here only for sensitivity analysis purposes and does not necessarily represent a realistic forest management scenario.

Figure 3-6 displays the same results in a different manner, allowing for further interpretation of the sensitivity analysis. The CP results under "extreme" weighting scheme are not displayed in Figure 3-6 as it is not realistic to use this weighting scheme in actual decision making procedures. The columns in Figure 3-6 represent the management alternatives (in tree basal area) ranging from 6 – 45 m^2/ha, whereas the individual rows represent the CP results under different weighting schemes and metric parameter "p" values. The most preferred vegetation management alternatives - in terms of the decision variable values - under a given weighting scheme are colored in dark green. As the colors shift from dark green to yellow and oranges, the stand densities become increasingly too dense to satisfy all management objectives simultaneously. On the other side, as the colors shift from dark green to green, blues and purple, the stand densities decrease steadily and satisfies all management objectives less and less. Each change in color away from the dark green signifies a five percent decrease in the CP achievement level. Red and pink signify achievement levels of less than 80%, either on the increasing or decreasing trends in tree basal area, respectively. The same color coding is used later in the ArcGIS analysis.

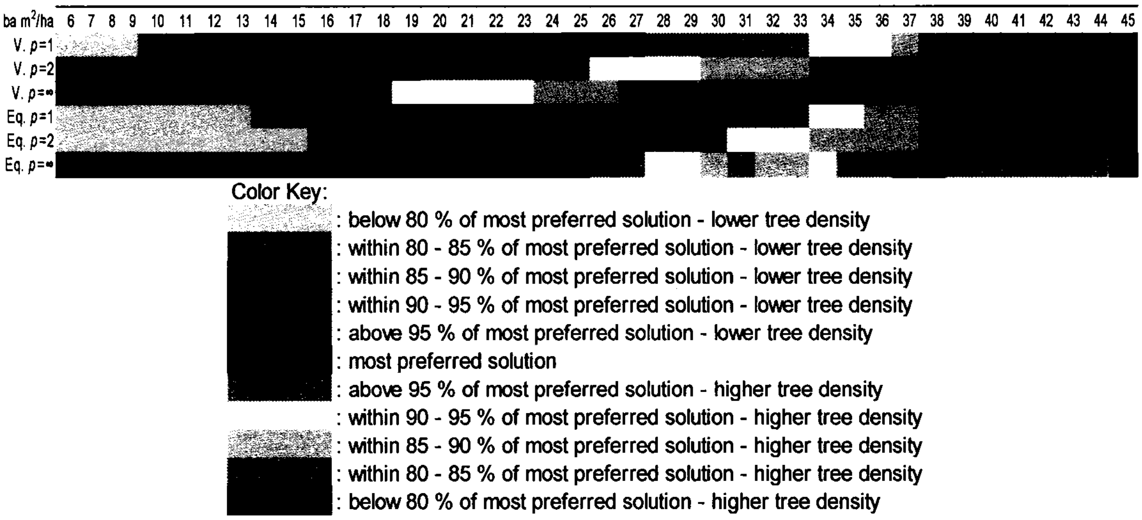

Figure 3-6: The columns represent the varying decision variable values, whereas each row represents CP results under different weighting scheme and *p*-values. The most preferred solutions for a given weighting scheme are colored in a dark green. "V" indicates varying weights assigned to the different management objectives and "Eq." indicates weighting all objective categories equally.

The results displayed in Figures 3-3, 3-4, 3-5 and 3-6 indicate that the MODM technique employed in this modeling effort is sensitive to both the decision makers' preference structure (expressed in the form of weights) and the p-metric values. This is especially true for $p = 2$ and ∞ and all weighting schemes. At the same time the technique is robust because it does not allow one set of weights to strongly influence any solution under $p = 1$. Figure 3-6, in particular, shows using $p = \infty$ is not useful in determining a particular most preferred vegetation management alternative that satisfies all 20 objectives simultaneously.

3.5 ILLUSTRATIVE EXAMPLE RESULTS

To illustrate the application of the modeling effort presented in this paper, the most robust parameter value of $p = 1$ and equal objective weights were used to analyze the problem using CP. The CP analysis suggests a most preferred tree basal area of 27 m^2/ha (see Figure 3-6 and Table 3-3). Table 3-4 lists the resulting objective function values for the 20 management objectives under the most preferred tree basal area treatment. The last two columns of the table also show the best and worst objective function values used in CP analysis.

A target basal area of 27m^2/ha was chosen with a "thinning-from-below"-prescription for the FVS simulation. Sample results of the modeling effort for each individual stand in the project area through time are displayed spatially in Figure 3-7. Only one treatment was simulated in 2007. Figure 3-7a shows the achievement level the individual stands in the project area belong to prior to the simulated treatment. Figure 3-7b illustrates the same immediately following the simulated treatment. Because trees have the tendency to grow, stand densities are generally expected to increase. As time progresses the performances of most individual stands change adversely with increases in their tree density (Figure 3-7 c-f). Only forest stands which had a stand density below the most preferred solution, as suggested by CP, eventually grew into the most preferred solution and at times may continue to grow beyond it. Table 3-5 indicates that the simulated treatment for 2007 reduces the forest stand areas classified as "too dense" (less than 90% of the achievement level) by about half. Areas with a stand density below the target basal area remained untreated and grew through the most preferred tree density level with time.

Table 3-4: Values for each one of the 20 forest management objectives corresponding to the most preferred vegetation management alternative under p = 1, 2 and ∞. The best and worst values for each objective are also shown in the last two columns, respectively. Because there are multiple preferred management levels of 6, 25, 38 and 45 m^2/ha for $p = \infty$, only the values for 6 and 45 as well as 25 are shown. The values for 25 m^2/ha is the same as for 25 m^2/ha and p = 2.

Criteria	*Criterion Scale*	*p = 1*	*p = 2*	*p = ∞*		*Best*	*Worst*
		27 m^2/ha	*25 m^2/ha*	*6 m^2/ha*	*45 m^2/ha*	*Value*	*Value*
Scenic Beauty Index	Ordinal (1-3)	2.38	2.39	1.34	1.71	2.39	1.34
Willingness-to-pay[1]	US$/Ha	66.67	67.62	0.00	0.00	67.45	0.00
Willingness-to-pay[2]	US$/Ha	17.66	17.87	0.00	0.00	17.87	0.00
Beetle Attacked Trees	% of BA Killed	1.62	1.54	0.72	2.19	0.72	2.19
Bark Beetle Rating	Ordinal (1-12)	6.89	6.45	2.31	10.81	2.31	10.81
Dwarf Mistletoe Rating	10-yr Infection Rate	1.05	1.02	0.77	1.28	0.77	1.28
Individual Exotic plants	Plants/HA	8.95	9.63	25.79	3.96	3.96	25.79
Amount of Herbage	kg/HA	139.22	164.63	1298.64	59.65	1298.64	59.65
Timber Yield	m^3/Ha	107.77	102.03	29.58	143.40	143.40	29.58
Cost of Tree Removal	US$/Ha	594.54	660.60	1288.17	1.35	1.35	1288.17
Crown Fuel Load	t/Ha	8.81	8.13	1.67	14.93	1.67	14.93
Heat Intensity	kJ/m^2	99.51	91.38	40.39	309.11	40.40	309.11
Crown Fire	% Crown Burned	41.73	37.00	8.58	98.38	8.57	98.38
Sediment Yield	t/Ha/yr	5.64	6.32	12.78	0.00	0.00	12.78
Streamflow	m^3/sec	8.79	9.27	17.44	6.76	17.44	6.76
Peak Flow	m^3/km^2	48.19	50.27	70.03	29.47	29.47	70.03
Abert Squirrel Habitat	Ordinal (1-5)	1.81	1.72	1.03	2.69	2.69	1.03
MSO Habitat	Ordinal (1-5)	1.27	1.08	0.00	2.79	2.79	0.00
Mule Deer Habitat	Ordinal (1-5)	3.69	3.87	3.41	3.02	4.32	2.85
NGH Habitat	Ordinal (1-5)	3.00	2.59	0.00	1.78	3.87	0.00

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[1] Willingness-to-pay for forest conditions based on forests as a cultural resource

[2] Willingness-to-pay for forest conditions based on forests as a recreational resource

Table 3-5: Summary of number of hectares of the project area falling into the various achievement levels (for equal weights and a p-value of 1).

Achievement Level	Prior Tx land in ha	2007 land in ha	2067 land in ha	2127 land in ha
▒	1,024	1,024	507	286
■	607	607	77	82
■	1,485	1,485	267	38
■	2,030	2,030	767	307
■	3,091	3,091	2,455	774
■	1,380	1,494	1,431	685
■	3,960	4,952	3,189	1,383
□	1,432	1,716	3,292	1,626
▒	1,339	721	2,400	1,397
■	364	188	1,752	1,282
■	1,180	583	1,754	10,063

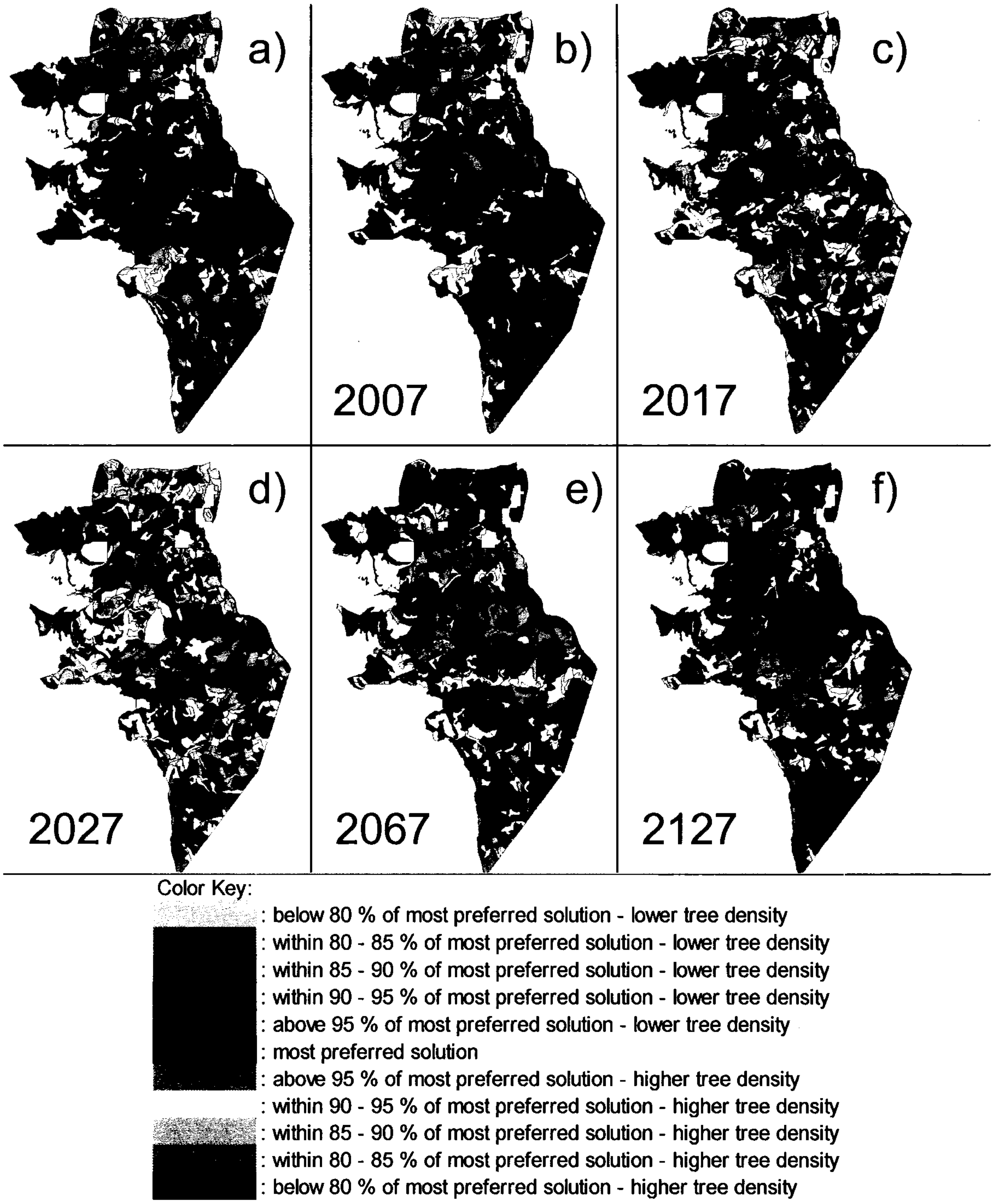

Figure 3-7: Different levels at which individual forest stands in the project area meet all management objectives simultaneously under equal weights and the *p*-value of 1. a) Prior to treatment b) At the time of treatment in 2007; and c) through f) represent the simulated performance at the indicated time steps. White areas are either indicative of non-Forest Service lands or non-ponderosa pine dominated stands.

3.6 CONCLUSION

The modeling effort presented in this paper uses a MODM technique in a temporal and spatial framework. Twenty objective response functions related to one specific stand density decision variable, tree basal area (in m^2/ha), are constructed to represent various ecosystem components. The 20 response functions are then evaluated using CP to: (1) determine the most preferred decision variable value, and (2) to assign a level of closeness to an ideal solution for stand densities that did not represent the most preferred solution. FVS was employed as the temporal component, to project the values of the decision variable in the study into the future under a variety of other variables that influence the future development of the decision variable. GIS was used next to assign an achievement level to polygons representing forest stands, based on the decision variable. This was done in a series of time steps and the results were displayed spatially as they changed through time.

Even though only 20 objective response functions are presented here, it does not mean that DMs or land managers need to or choose to give very much importance to all of the objectives. New objective response functions can be added or replace existing ones to make the analysis more holistic as new information becomes available. In the modeling effort presented here, the 20 response functions received equal, varying and extreme weights, and used the with p-metric parameter values of 1, 2 and ∞ to determine the sensitivity of the CP technique to changing weights and *p*-values. The results indicate that the MODM technique employed in this modeling effort is sensitive to both the decision makers' weights and the p-metric values. At the same time the technique is robust. To better illustrate this point the following chapters of this dissertation present a case study using this modeling effort and actual FVS simulations and weighting preferences by real DMs.

The output from CP indicates that the most preferred tree basal area when all objectives have equal weights and under a *p*-value of 1 is 27 m^2/ha. When the individual management alternatives (expressed in tree basal area) are evaluated in terms of their level of closeness to the most preferred alternative (Figure 3-6), the differences between the preference structures becomes more apparent. However, the technique is easy to use. Because CP uses a straight forward computation it can easily be handled using a spreadsheet.

The use of FVS as the temporal modeling component in the modeling process has several advantages. Generally the software is widely used by land managing agencies, such as the US Forest Service and is easily understood and trusted by DMs and stakeholders (Dixon 2002). The interactiveness of the modeling effort presented in this paper allows analysts to plug in FVS simulations results to receive a spatio-temporal MODM output with very little extra effort.

The advantage of this model, compared to other growth and yield models described in the literature (Miner et al. 1988, Edminster el al. 1991, Dixon 2002) is its ability to visually display how well numerous forest ecosystem management objectives are met simultaneously on a forest stand basis, across an entire project over a landscape. It allows DMs and land managers to see into the future, which stands may require additional treatment and which stands do not. However, one short coming of this modeling effort there is no interactiveness at the GIS stage among the spatially distributed results. While FVS takes interactions between different forest stands into account, GIS does not. The displayed analysis results are purely based on the basal area calculated in CP and then simulated in FVS. This issue should be explored in future modeling efforts.

Today's computing power allows us to realize concepts that in previous decades had been just that: Concepts. ArcGIS Modelbuilder, for example, allows the user to combine the outputs of the MODM technique CP analysis results with those of the dynamic forest vegetation growth simulator FVS and display them on a stand by stand basis across the entire landscape the project covers. In other words, it allows us to model southwestern ponderosa pine forest ecosystem management in a spatio-temporal multi-objective decision making framework.

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CHAPTER 4 – SPATIO-TEMPORAL MULTI-OBJECTIVE DECISION MAKING IN FOREST MANAGEMENT: CONCEPTS

Abstract: Forest ecosystem management is the art and science of making decisions that involve numerous cultural, social, economic and environmental components interacting with one another. Forest managers model environmental, physical, biological or economic components, such as tree growth, fire behavior or the price of timber. In this paper, the Multi-Objective Decision Making (MODM) process in forest management is evaluated on spatial and temporal scales. A conceptual model intended for forest managers and decision-makers is assembled as a set of one MODM technique, mathematical response functions and two modeling programs – one spatial and one dynamic. Compromise Programming (CP) is the MODM technique utilized in this ecosystems modeling effort. Twenty-two mathematical response functions link forest management objectives to forest stand density, which is used as a decision variable. An individual-tree growth model (FVS), used by managers to develop silvicultural and land management plans, is used as the dynamic modeling component, whereas a Geographic Information System (ArcGIS) facilitates the spatial aspect of the modeling effort. The management of the ponderosa pine forest in north-central Arizona involves multiple interests and stakeholders with different, often conflicting expectations and management objectives. With the forest planning software available to us today and considering the complexity and number of variables involved it makes sense to use a spatio-temporal MODM framework. In this paper the author demonstrates how forest managers can identify numerous feasible forest management alternatives in terms of reduction of the vegetation density, as well as to what extent the identified management actions achieve the selected objectives over time and space.

4.1 INTRODUCTION

A forest ecosystem is a unique combination of faunal, floral and physical structures with numerous cultural, social, economic and environmental components that interact with one another. The management of such a system involves many individuals or groups of stakeholders and other interests with different objectives that often conflict with each other (Bare and Mendoza 1988). The management objectives related to commodity and amenity resources that change with time and space and may be expressed quantitatively or qualitatively in the form of ordinal or cardinal data (Kennedy and Koch 2004, Thomas 2006). Because these objectives apply to forest ecosystems that change with time and across landscapes (Buongiorna and Gilles 2003), the most appropriate management is adaptive, dynamic, spatially varied and multi-objective in nature.

Models are abstract representations of the real world and are often informal, intuitive and supported by experience of people running them. What is needed in today's forest ecosystem management is a transparent method that addresses the multiple objectives of management actions across spatial and temporal scales. Any model that describes the variation of one or more phenomena over the Earth's surface is a spatial model (Goodchild 2005). Geographic Information Systems (GIS) are particularly developed platforms to handle spatial modeling. If modeling goals include describing past behavior or predicting future outcomes of management policies or actions on entire landscapes, spatial or geographic modeling is essential (Risser et al 1984, Costanza et al. 1990, Sklar and Constanza 1991, Constanza and Voinov 2003, Maxwell and Voinov 2005). However, modeling ecosystems at a landscape scale is a complex process, which can be simplified using state-of-the-art modeling software. Such modeling software and techniques must allow new users to recognize major interactions and to be adaptive and transparent, because decision makers and stake holders are unlikely to trust a model that they don't understand (Maxwell and Voinov 2005). The general objective of landscape modeling is to predict changes in land cover patterns across large geographic regions over long time scales as a result of various site-specific management alternatives and natural changes (Costanza et al. 1990). Probably the best-known example of a forest ecosystem model on a landscape scale is the Forest Ecosystem Management Assessment Team's Management Plan for Old-Growth Ecosystems within the range of the Northern Spotted Owl in the Pacific Northwest of the United States (Vogt et al. 1997). While FEMAT (1993) suggested four spatial scales, namely regional, physiographic province, watershed and specific site, other authors disagree. Körner (1993), Levin (1993), and Reynolds et al. (1993) have suggested that the primary consideration of an ecosystem management should be the identification of scale at which manageable ecological processes occur. Because units of forest ecosystem scales do not have functional boundaries, physical boundaries can be delineated based on management objectives (Vogt et al. 1997).

The southwestern ponderosa pine (*Pinus ponderosa var. Scopulorum*) forest ecosystem, which is the focus of this paper, has been relatively stable for the past several hundred years (Swetnam 1990, Swetnam and Baisan1996). Recent extremes in climatic weather and fire patterns can potentially lead to regime shifts that may be irreversible (Folke et al. 2004). Hence, it is very important to have models that land managers and decision-makers can use as tools to make good management decisions at the landscape scale and in the face of major uncertainties on how ecosystems respond to increasing human use (Steffen et al. 2004) and other disturbances (Jackson et al 2001, Paine et al. 1998).

While GIS has advanced by leaps and bounds over the past two decades, the question of how we must deal with time and space has paralleled its development and has raised the demand for close collaboration between GIS and mathematical modeling (Peuquet 2002). Static models are often used as indicators to combine various inputs to create useful outputs (Goodchild 2005). For example, mapped properties such as tree density, canopy closure, downed woody debris, slope and other forest stand properties will give us estimates about the geographic variation and vulnerability of forest stands to fire potential. Dynamic models, however, represent a process that modifies or transforms some aspect of the forest through time. Even though dynamic simulation models today are used in fields ranging from biology to engineering and business, most of them are not designed to simulate geographically-distributed systems, because applying such a general purpose simulation model as a geographic information system is very difficult, making dynamic GIS modeling currently more a concept than a practical reality (Miller et al. 2005). Most spatial models do not deal with dynamic processes per se. Instead they measure, analyze, and simulate associations and relationships with variables at a particular cross section in time that is between multiple points rather than through time in a continuous fashion (Batty 2005).

Burrough et al. (2005) define a dynamic spatial model *as a mathematical representation of a real-world process in which the state of a geographic field or object changes in response to variations in the driving force*. Over the past ten years, GIS toolkits have been developed to address many of the generic aspects of space-time modeling, such as PCRaster (Burrough et al. 2005). However, *many scientists have approached the problem of modeling dynamic aspects of environmental processes by writing individual models using standard languages such as FORTRAN and C++, which could be interfaced with GIS. These models are often difficult to maintain and modify, particularly if the original author is no longer working in the team* (Burrough et al. 2005).

Yet, it is important to include a time component in the analysis of environmental problems, where pattern changes respond to external forces, such as land cover changes. Further, any system that models space-time processes *must include procedures for discretizing space-time and for the computation of new attributes for the spatial and temporal units in response to the driving force* (Burrough et al. 2005). It is also essential to choose the correct spatial and temporal resolution, because variations that occur within the dimensions of the cell or polygon will not be registered by either the data or the process. Temporal changes in attributes of cell values can be computed for single cells or for neighboring cells of varying size and shape. Once a model is set up and run, the changes can be visualized as a film, providing extra understanding of the processes being modeled (Burrough et al. 2005). Here a spatio-temporal MODM model becomes a useful tool that can synthesize the challenges land managers and decision-makers face and to allow them to address these challenges in a dynamic and adaptive framework at the landscape scale.

4.2 THE SOUTHWESTERN PONDEROSA PINE FOREST ECOSYSTEM

The southwestern ponderosa pine forest ecosystem is considered to be the largest continuous stand of its kind in the U.S. It stretches from southern Utah through northern and central Arizona to south central New Mexico. This area constitutes about half of the 6.5 million ha of ponderosa pine forest ecosystem in the Rocky Mountains (USFS 1989). Over 65% of this forest ecosystem is under National Forest Ownership (Conner et al. 1990), while the rest is in private, tribal, state and National Park ownership. The current distribution of ponderosa pine is mostly affected by climatic factors, such as precipitation and temperature gradients, as well as fire regimes. However, anthropogenic influences such as grazing and fire-suppression have also some influence on its distribution and density (Covington et al. 1997). While some wildlife species require management practices that maintain a high density to provide nesting, bedding, hiding and escape cover (Wagner et al. 2000), this same dense vegetation presents a management problem for reducing the risk of wildfires, and the spread of tree diseases and pathogens. Under these conflicting situations the ponderosa pine forest ecosystem managers are often asked to achieve specific societal objectives while being required to meet ecological and economic constraints.

Public distrust in the Federal government and its bureaucratic decision-making processes let to laws, such as the 1970 Clean Water Act, the 1973 Endangered Species Act, the 1976 Federal Land Policy and Management Act, and the Government Performance and Results Act of 1993. These legislative acts have mandated public input and are aimed at limiting the decision-making discretion of federal land management agencies, such as the USDA Forest Service (USFS). In these laws individuals, businesses and environmental NGOs have legal recourse in any land-management process. However, with the number of catastrophic wildfires that are mounting in the western US, the public is looking for ways that are less legalistic and technical to engage the USFS in their decision-making processes. A recent survey in north-central Arizona found that the public, in general, has the desire for the USFS to continue to manage the forest systems for values other than commercial timber, especially as it restores the forest to its less dense landscape form (Ostergren et al. 2006). Many are expecting the USFS to play a more active role in communicating with and involving the public. The modeling effort presented in this paper provides an avenue to help the USFS make clear, objective and transparent forest management decisions.

4.3 THE UPPER BEAVER CREEK WATERSHED FUEL REDUCTION PROJECT

An example of a USFS project in north-central Arizona that could benefit from more public involvement is the Upper Beaver Creek Watershed Fuel Reduction Project (UBC). The primary purpose of the UBC project is to reduce the risk for stand-replacing wildfire occurrence that would threaten people, private property and natural resource values. The USFS management team responsible for achieving these goals believes that the most effective way to do so is to begin restoring this fire prone ecosystem to as close as possible to pre-European settlement conditions (USFS 2006).

The intent of the project is to show positive changes from the existing undesirable conditions to some desired future conditions and show improvement in the overall forest fire regime and forest conditions (USFS 2006). Past research work has shown that forests thinning to remove fuel loads are less likely to result in stand-replacing crown fires (Fulé et al. 2001, Omi and Martinson 2002). Hence, the USFS's proposed actions consist of a variety of vegetation management, fuel reduction, and prescribed burning activities over the next 20 years to reduce the potential for stand-replacement wildfire and to begin restoring the forest to a fire-adapted ecosystem. A detailed description of the proposed actions is given in the "Upper Beaver Creek Watershed Fuel Reduction Project: Proposed Action Report" (USFS 2006). The proposed actions are designed to comply with Forest Plan standards and guidelines, as amended (USFS 1987).

The desired condition for the Upper Beaver Creek Watershed Fuel Reduction Project area are defined by the Coconino National Forest Plan (USFS 1987) as a landscape where the fire conditions are moving toward or achieving the desired fire regime that is appropriate for the vegetation type within the ecosystem. This is a relatively vague description and leaves the definition of "the desired condition for the ponderosa pine type" up to USFS interdisciplinary (ID) team interpretation. While the professional experience of the ID team may be extensive, their value judgments may lack objectivity and transparency, leaving other groups and stakeholders in the project area to question the specifics of the USFS ID team's decisions. Even though the ID team consists of experts from various disciplines, this lack of transparency and objectivity in the decision making process can make it difficult to defend their decisions in court. Because the Forest Service manages public lands, its management decisions are often subject to lawsuits (Keele et al. 2006). Such lawsuits have prevented fuels treatment actions from being implemented in forests, which as a consequence have experienced catastrophic wildfires, especially in Arizona (Ostergren et al. 2006). Most members of Wildland Urban Interface (WUI) communities in Arizona understand the benefits of fuel reduction treatments. However, there is a high influx of people from other communities who are not as familiar with the forest ecosystem in north-central Arizona (Ostergren et al. 2006), which would benefit from a more open decision-making process by the USFS. Even long-time residents, who previously distrust USFS decisions, would be more likely to accept USFS decision, if the decision making process was more transparent (Ostergren et al. 2006). A modeling effort, as the one suggested in this paper, is objective, transparent and therefore defensible in legal and social settings. The MODM technique in itself is objective, because it converts the management objectives, both quantitative and qualitative, into mathematical response functions, which have no emotional values attached to them. Transparency is achieved by disclosing the decision makers' preference structure in the form of the weights that are assigned to the various management objectives in the given project area. Weights signify the importance of one objective relative to another objective. This transparency allows members of the affected communities to see how the experts arrive at their decisions, by externalizing this otherwise internal process.

4.4 TERMINOLOGY

Some terms and expression used in this paper have different meanings for different readers. Hence, this is a section that defines these terms and expressions as they are referred to and understood by the author. The *Achievement Level* is an indicator of how well a forest stand meets the most preferred solution given the management objectives. An *Alternative* in this paper refers to the tree density expressed in basal area (BA), which also happens to be the *Decision Variable. Compromise Programming (CP)* is a distance based technique used for evaluating a multiple objective management problem to arrive at a compromise and fair solution. (Tecle et al. 1988). A *Management Objective* is understood to be the desired forest management direction, such as slowing the spread of Dwarf Mistletoe (DMT) or maintaining or increasing habitat for Mexican Spotted Owl (MSO). *MODM* or Multi-Objective Decision-Making, is a technique for arriving at a management decision that satisfies multiple objectives, or that satisfies the desires of multiple decision makers. *Objective Weights* are a set of weights that have been applied to all management objectives to represent a Decision Makers' (DM's) preference structure of the objectives. A *Response Function* is a mathematical formulation of a management objective or forest ecosystem component response to certain management action(s). In this paper a *Simulation* represents the outcome of forest vegetation growth as predicted by the Forest Vegetation Simulator (FVS) after thinning and prescribed burn treatments have been applied.

4.5 METHODOLOGY

The modeling approach in this study consists of developing many objective response functions, generating two sets of objective weights and using three different models. The latter consist of one MODM technique, a vegetation growth model and GIS software to evaluate the objective functions in an integrated manner through time and space. The outcome of the modeling effort is expected to assist forest resource managers to arrive at a fair, balanced and generally acceptable forest ecosystem management scheme. The objective response functions link the wishes and aspiration of decision makers to the density of forest stands expressed in tree basal area. The MODM technique used is Compromise Programming (CP), while the vegetation growth model and the GIS software are the Forest Vegetation Simulator (FVS) and ArcGIS. FVS is an individual-tree growth model used by forest managers to help in developing land management plans. ArcGIS is a Geographic Information System, used by land managers, other decision makers and analysts for creating, storing, analyzing and managing spatial data and associated attributes.

Advances in computer hardware and software engineering over the past few years have allowed the integration of comprehensive land resources management and spatial analysis modeling on a single platform to visually interpret joint resource management outcomes. However, dynamic system simulation, research optimization in operations and visualization of multidimensional data are still neglected areas (Maguire 2005). To address this issue, achievement levels for each stand within the project area were tied to GIS and mapped spatially so users can view the projected outcomes over time. GIS are relied upon because they are one of the most effective ways of communicating spatial data. This is especially important when communicating a spatial problem to variety of stakeholders and DMs, particularly when the problem at hand can be represented digitally (Batty 2005). Because GIS systems are intrinsically visual, Euclidian space can be clearly and simply represented in two and three dimensions.

The modeling effort demonstrated in this paper provides results at three stages: (1) the MODM stage; (2) the temporal projection stage; and (3) the spatial (GIS) stage (see Figure 4-1). Even though the user of this model is ultimately interested in the output at the last stage, the interactiveness of this process allows the modelers to make modifications at either of the first two stages: the MODM stage and the temporal projection stage.

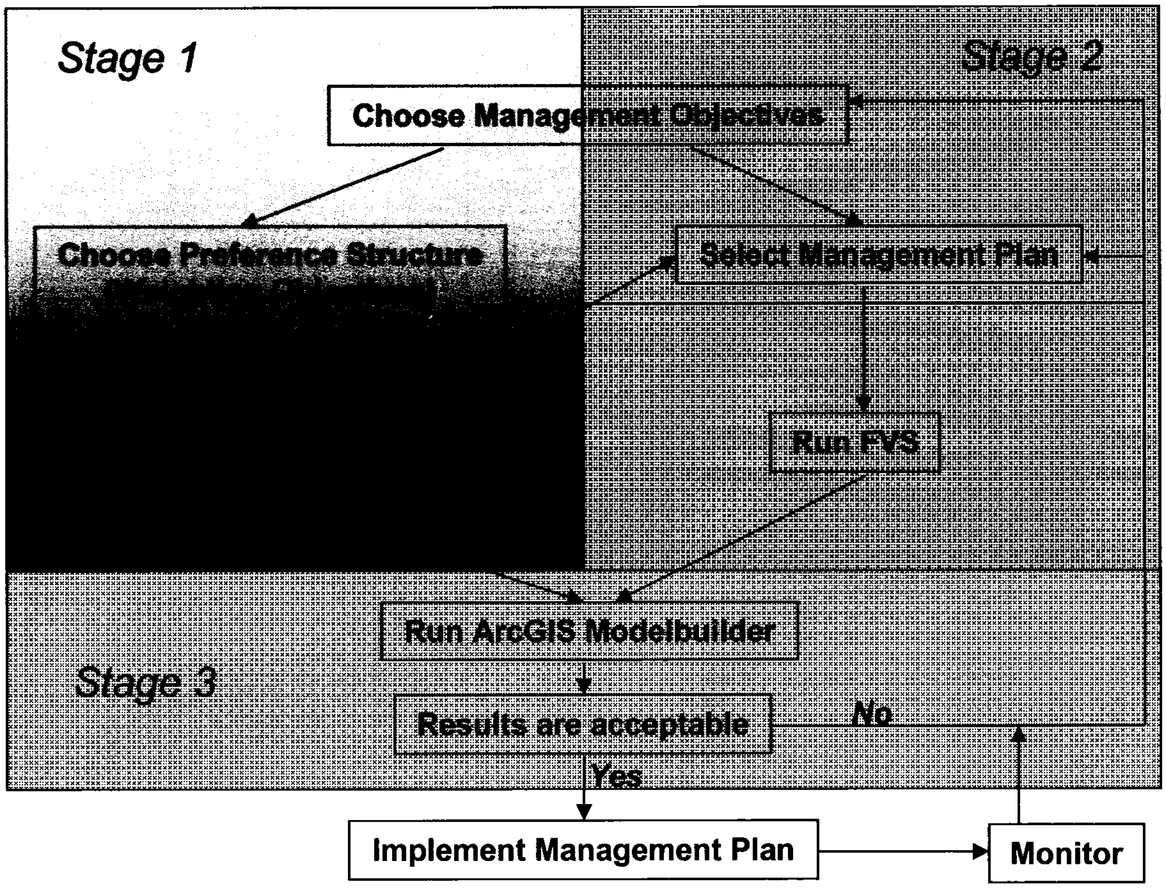

Figure 4-1: This flow chart illustrates the three stages of the modeling effort. In the first stage the MODM technique is used to determine a preferred management plan on the basis of management objectives and the sets of preference structures. In the second stage FVS is run based on the management objective values and the selected management plan. In the final stage ArcGIS Modelbuilder is run using the FVS and CP outputs as inputs. The results can then be evaluated, and if acceptable, be implemented and monitored. If the solution is not acceptable by the DM(s), then the management objectives, preference structure and/or the selected management plan may be modified after either of these steps as part of the greater scheme of adaptive management.

4.5.1 Compromise Programming

Compromise Programming is well described in detail in Chapter 3 of this dissertation and in several pieces of literature (Poff 2002, Tecle et al. 1988, Tecle and Duckstein 1993, Zeleny 1973, 1982). It is based on the concept of distance to arrive at a most satisfying solution. Here, distance is used as a proxy to measure human preference. The preferred solution is the closest of non-dominated solutions to an infeasible ideal point (Zeleny 1973). A non-dominated solution in a MODM problem is one that does not show any improvement in any one of the objective solutions without making at least one other solution worse (Tecle et al. 1988, Tecle and Duckstein 1993), while an ideal point represents the joint location of the maximum solutions of all individual objectives optimized separately. Therefore, arriving at a compromise solution can be viewed as minimizing a DM's regret for not obtaining the ideal solution. Weights are assigned to individual management objectives to signify the importance of one objective relative to the other objectives. Weights are assigned by the DMs and/or stakeholders.

The general formulation of a CP technique is expressed as follows:

$$\min \{l_{\mathrm{p}} = [\sum_{i=1}^{I} W_{\mathrm{i}}^{\mathrm{p}} (Z_i^* - Z_{ij})^{\mathrm{p}}]^{1/\mathrm{p}}\}, j = 1,\ldots, J \qquad [1]$$

Here l_p is the distance metric, for any p in which $0 < p < \infty$. It is the measure of a solution's closeness to the ideal point Z^*, which is the set of all the maximum values of all objective functions. Z_{ij} is the value of objective i under a specific discrete value of decision variable j. I is the number of objectives within categories and may range from one to four. J is the number of discrete decision variable values. Z_i^* is the maximum value for objective i. To avoid scale effects and to make all objective function values commensurable, the objective functions are normalized by dividing the right hand side by the expression $Z_i^* - Z_i^{**}$, where Z_i^{**} is the worst value of objective i. The normalized objective functions are expressed in the following manner:

$$Z_{ij} = (Z_{ij} - Z_i^{**}) / (Z_i^* - Z_i^{**}), i = 1,\ldots, I \text{ and } j = 1,\ldots, J \qquad [2]$$

where the Z_{ij} on the left hand side of the equation represents the normalized elements of the original pay-off matrix Z_{ij} on the right hand side of the equation. This normalization process guarantees the Z_{ij} on the left hand side of the equation to have values between 0 and 1.

The weight W_i in equation [1] signifies the importance of objective i relative to the other objectives. The p is the metric parameter. Different values of p represent different aspects of a compromise programming algorithm. For $p = 1$, all deviations from Z_i^* are directly proportional to their magnitude. For $2 \leq p < \infty$, the largest deviation has the greatest influence. Varying p from 1 to ∞, allows to move from having a perfect compensation among the objectives (i.e., minimizing the sum of individual regrets) to having no compensation among the objectives in the decision making process (i.e., minimizing the maximum regret). The greater the conflict between different DMs is, the smaller the possible compensation (Zeleny 1974, 1982; Goicoechea et al. 1982; Szidarovszky et al. 1986).

4.5.2 Objective Response Functions

In general, an objective represents a forest ecosystem component's response to management, the cost of management or societal need of the forest system. The specific objective functions considered in this study are described in Table 4-1. They are all functions of one decision variable, tree basal area (TBA in m^2/ha and ft^2/ac), representing forest density. The process by which individual response functions are selected and created can be either internal or external to the MODM process and is mostly dependent on the availability of data related to the decision variable. The response functions used here had been created a priori and therefore can be considered external to the MODM process.

The decision variable of TBA used here has values that range from 6 through 45 m^2/ha (26-196 ft^2/ac). A TBA of in 6 m^2/ha is the minimum acceptable density level for the forest in the study area to qualify as “a forest” by the United Nations Food and Agriculture Organization (FAO) guidelines (FAO 2006). The average upper limit of the majority of the data available for which response functions have been created is 45 m^2/ha (Poff 2002). Using TBA as the decision variable has several advantages: (1) Availability of data related to many management objectives or ecosystem functions for constructing response functions; (2) many forest-land managing agencies use TBA to quantify management activities; (3) TBA is one of the major decision variables used in FVS, which is also utilized in this modeling effort. The disadvantage is that TBA does not make any distinction between the conditions of some forest characteristics such as clumpiness or age distribution. However, other forest characteristics, such as trees per hectare or percent of canopy closure have a good relationship to TBA in the southwestern ponderosa pine forest and it can easily be converted to either (Severson and Medina 1983, Rupp 1995). Stands in north-central Arizona are defined by past management actions, mostly consisting of logging. Because of past logging practices typical for the area, most stands do have a heterogeneous age distribution and class sizes, which are desirable in this ecosystem.

The objective response function values are normalized to avoid scale effects and to make all objective function values commensurable. To determine the most preferred forest management alternative in terms of its ability to achieve the desired objectives, the twenty-two objective response functions are sorted into nine objective categories on the basis of their similarity in addressing related issues. For example, risk of flooding, water yield and quality are combined into a *desired hydrologic condition* category (see Table 4-1).

Compromise programming is adapted here to perform a two-level evaluation of vegetation management actions based on TBA. The first level involves trade off analysis within each of the nine objective categories consisting of more than one management objective. Then a second-stage evaluation is performed to produce a trade-off analysis among the nine categories. Another feature of CP is that it allows the analyst to select a distance parameter p. Varying p from 1 to ∞, allows the analyst to move from having a perfect compensation among the objectives (i.e., minimizing the sum of individual regrets) to having no compensation among the objectives (i.e., minimizing the maximum regret) in the decision making process. The greater the conflict between different DMs is, the smaller the possible compensation (Zeleny 1974, 1982; Goicoechea et al. 1982; Szidarovszky et al. 1986). The p-values of 2 and 1 were used in the first and second level of the CP, respectively. A more detailed explanation and description of this CP process and a sensitivity analysis is given in Chapter 3.

4.5.3 Articulation of the Preference Structure

In this study, the members of the Mogollon Rim Ranger District Interdisciplinary (ID) Team assigned weights to the different management objectives and their criteria specified in Table 4-1. The ID Team consisted of a Team Leader and one person each from fire management, weeds control/understory vegetation, silviculture and two wildlife habitat management experts. The members of the ID team were instructed to assign two sets of weights. The first set are within category weights (WCW) (see Table 4-1), which are used in the first level of the trade off evaluation process, where a compromise solution is found within each objective category. If an objective category only had one objective this step is skipped. The second set of weights is assigned to the objective categories (see Table 4-1 columns 1 through 5). These weights are used in the second level of the trade off analysis procedure to arrive at the best solution, in terms of TBA.

Table 4-1: Weights range from 1 to 10; where 1 indicates the objective has the least weight in the decision making process; 10 indicates the objective has the maximum weight. The values given in this table represent the preference structure of the UBC ID Team. P = Project, F = Fire, S = Silviculture, WL= Wildlife, WC = Weed Control

Weight					Objective	Objectives	Criteria	WCW				
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
P	F	S	WL	WC	Categories			P	F	S	WL	WC
3	3	6	1	2	Maximize Social Benefits	Aesthetic Quality	Visual	5	5	5	1	5
						Cultural Resources	Tree Density	4	5	10	1	5
						Recreational Use	Willingness to pay	1	1	5	1	1
9	1	9	5	9	Minimize Insects & Diseases	DMT Infection	DMR	5	1	9	3	6
						Pine Beetle	Attacked Trees	8	1	9	3	6
						Bark Beetle	Hazard Rating	8	1	9	3	6
5	5	8	5	8	Min Exotics	Exotic Plants	Plants/ha	N/A				
5	1	7	7	7	Max Forage	Herbage Production	Amount of Herbage	N/A				
7	1	4	1	3	Max Timber	Timber Growth	Timber Yield	N/A				
4	5	2	1	4	Min Costs	Costs	Cost of Thinning	N/A				
10	10	10	5	10	Minimize Fire Hazard & Effects	Forest Fire	Crown Fuel	9	10	10	5	8
							Crown Fire	10	10	10	5	8
							Heat Intensity	5	10	10	5	10
6	3	3	8	5	Desirable Hydrological Condition	↓ Flood Hazard	Peak Flow	3	3	5	10	1
						↑ Water Yield	Streamflow	2	1	5	10	4
						↑ Water Quality	Sedimentation	6	5	5	10	5
8	5	5	10	10	Optimize Wildlife Habitat	Non-Game Species	Abert Squirrel	7	5	7	8	8
						Game Species	Deer (*spp.*)	6	10	7	8	2
							Elk	1	5	7	1	1
						Predator Species	Mex Gray Wolf	1	1	7	10	1
						Threat./Endang.	MSO	8	5	7	10	8
						USFS Sensitive	N. Goshawk	7	5	7	10	8

The weights shown in Table 4-1 represent the preference structure of the UBC ID Team. The members of the ID Team were asked to assigned weights on the basis of their preferences on the objectives to be optimized. (i.e.: The wildlife experts used the weights to reflect how they would measure the relative importance of all the management objectives, if the project area was primarily managed for wildlife.) CP was then run for the 4 remaining preference structures in the same manner as for the project. This allows for a comparison and analysis how well the CP results for the project fair compared to scenarios where the project area was primarily managed for fire prevention, wildlife, silviculture or weed control/understory vegetation.

4.5.4 Forest Vegetation Simulator

The vegetation growth model used to evaluate forest conditions with time in this modeling effort the USFS's Forest Vegetation Simulator (FVS). This is a forest management tool for predicting forest stand dynamics. It can be utilized to summarize current stand conditions, to simulate future stand conditions under various alternative management scenarios (Dixon 2002) and the resulting output can be used as input into forest planning models as well as other analysis tools such as geographic information systems (GIS) (McMahan et al. 2002). A detailed description of the workings of FVS can be found in "Essential FVS: A User's Guide to the Forest Vegetation Simulator" (Dixon 2002) and "Forest Vegetation Simulator" (USFS 2005).

While FVS serves as the temporal projection tool in this study, any other software performing similar functions could be used instead, such as the Tree And Stand Simulator (TASS) (Mitchell 1975). However, FVS was chosen because it is used by the forest land management agencies in the Southwest and it simulates growth of southwestern ponderosa pine stands (Dixon 2002). In its most basic function, FVS computes future forest stand density based on an original, measured stand density given a set of variables.

The set of variables that influences stand growth projections includes physical variables such as slope and aspect, to biological variables such as tree mortality, and management variables such as thinning or prescribed burn treatments. Stand conditions, such as mortality are also influenced by conditions in neighboring stands. The USFS ID Team identified numerous burning and thinning prescriptions in the project area. The FVS simulated prescribed burning and thinning treatments over twenty years. The time scale for the simulation is 50 years with two year time steps for the first ten years and ten year time steps for the remaining forty years. Further details on the treatment descriptions can be found in the "Upper Beaver Creek Watershed Fuel Reduction Project: Proposed Action Report" (USFS 2006).

4.5.5 Geographic Information System (GIS)

ESRI's ArcGIS was used to handle the spatial analysis and display part of this MODM modeling endeavor. The ModelBuilder extension of ArcGIS allows the user to build a model using a diagram that resembles a flowchart (Krivoruchko and Gotway-Crawford 2005, Maidment et al. 2005, Miller et al. 2005) (see Figure 4-2). In this feature of the ArcGIS software, the model consists of a set of spatial processes that convert input data into an output layer. ModelBuilder itself is not dynamic in version 9.1, however, temporal components can be simulated by running the model multiple times, using a regular time step (Miller et al. 2005). This methodology was used in this study.

Here GIS was used to assign the level of closeness to polygons based on their TBA values. This measure of closeness of CP solution to the ideal point serves as a surrogate for the achievement levels of the management problem. Each layer represents a group of forest stands with a given *Achievement Level*, based on the CP results. Similar to surrogate for the achievement levels of the management problem. Each layer represents a group of forest stands with a given *Achievement Level*, based on the CP results. Similar to other spatial models, this step in Modelbuilder does not deal with dynamic processes per se. Instead it simulates associations of the achievement level with the decision variable TBA at a cross section in time between multiple points through time.

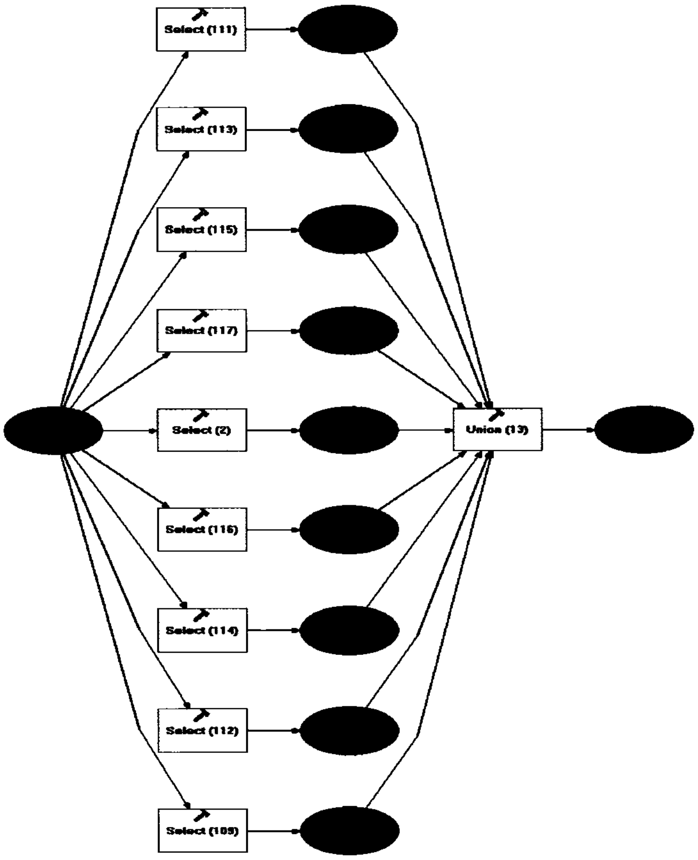

Figure 4-2: A flow chart of how ArcGIS ModelBuilder is used to create eleven output layers per time step.

Using the query function in Modelbuilder, eleven layers were created per weighting scheme per time step output given in the FVS table. The eleven layers per weighting scheme were grouped into one layer. This leaves one layer per time-step, which displays the 11 sub-layers, each representing a color coded achievement level of the given weighting scheme on a stand by stand basis. Values that were outside the

There are a total of eleven time steps in this simulation process: one every two years from 2006 – 2016; one every ten years from 2016-2056; plus the stand conditions in 2057. The 2057 achievement level layer represents the "no-action" alternative, simulating forest growth as if no treatment had been administered. The eleven sub-layers, for each time step, are color as shown in Figure 4-5.

4.6 RESULTS

The results of this modeling effort are two-fold: (1) The MODM technique arrives at a preferred tree basal area (TBA), based on DMs preference structure and the objective function values; (2) The FVS forest growth and treatment simulation provides the TBA on a stand level basis, which is then matched with the CP results in ArcGIS. This provides a visual representation of how well all management objectives are achieved simultaneously through time for the entire landscape of the project area.

4.6.1 CP Results

The management alternatives (in the form of stand density expressed in m^2/ha and ft^2/ac TBA) are the discretized version of the decision variable displayed on the x-axis in Figure 4-3. The y-axis is a standardized level of closeness, which ranges from zero to one, where 1 represents an infeasible ideal point. The trend curves in Figure 4-3 display the results of CP analysis under the five different ID Team preference structures. Each preference structure or weighting scheme of an ID team member is represented by one trend curve. The management alternative value under the highest point in each curve shows the most preferred forest stand density level with respect to all management objectives. The results, which are show in Table 4-2 indicate the sensitivity of the CP analysis results to weights. Besides giving us the most preferred basal area under each weighting scheme, Figure 4-3 shows that the “Fire” and “Silviculture” preference weighting schemes have higher levels of closeness than the weighting schemes that favor the other ID Team members. They also have more defined curvatures to them indicating a narrower range of acceptable TBA. The trend curve with the “Wildlife” favoring weights has the lowest level of closeness of all preference structures, mostly in the lower TBA range. This is probably due to the fact that the wildlife species considered by the response functions are forest species, which consequently do better in denser forest stands. However, towards the end of the lower TBA range, the wildlife trend curve begins to come up again indicating the need of some species to have forage at the lower forest density. It is also interesting that the best TBA for the wildlife biologist, is considered below 80% of the level of closeness by the silviculturalist and below 85% of the level of closeness by the fire manager. The trend curve with the weeds control/understory favoring weights has also some sinuosity to it, indicating the ID team’s favor of controlling weeds (higher TBA) and appreciation for desirable understory vegetation (low TBA). The trend curve with the more balanced project weights appears to favor stand densities that are good for wildlife habitat. The relative flat curvature of the project trend curve is also indicative of the address all management objectives, while the individual trend curves for the remaining preference structures are more to the point and have a very narrow range of the best possible basal area (see Table 4-2). These results indicate that the CP algorithm is somewhat sensitive to weights.

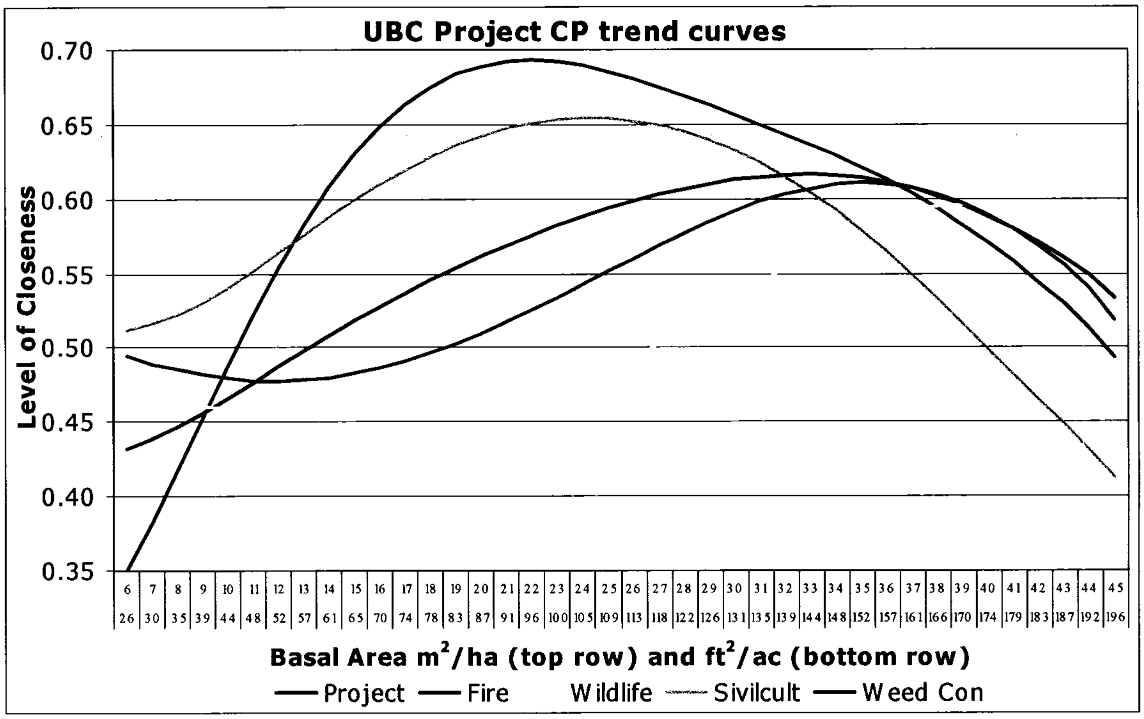

Figure 4-3: The sensitivity of the CP algorithm to changes in weights along the range of the decision variable values.

Figure 4-4 displays the same results in a different manner, allowing for further interpretation. The columns represent the management alternatives (in the form of stand density expressed in basal area) that range from 6 to 45 m^2/ha (or 26 to 196 ft^2/ac), whereas each row represents the different preference structures articulated by the ID team members. The most preferred vegetation management alternatives - in terms of the decision variable values - under a given weighting scheme are colored in dark green. As the colors shift from dark green to yellow and oranges, the stand densities become increasingly too dense to satisfy all management objectives simultaneously. On the other side, as the colors shift from dark green to green, blues and purple, the stand densities decrease steadily and satisfies all management objectives less and less. Each change in color away from the dark green signifies a five percent decrease in the CP achievement level. Red and pink signify achievement levels of less than 80%, either on the increasing or decreasing trends in tree basal area, respectively. The same color coding is used later in the ArcGIS analysis.

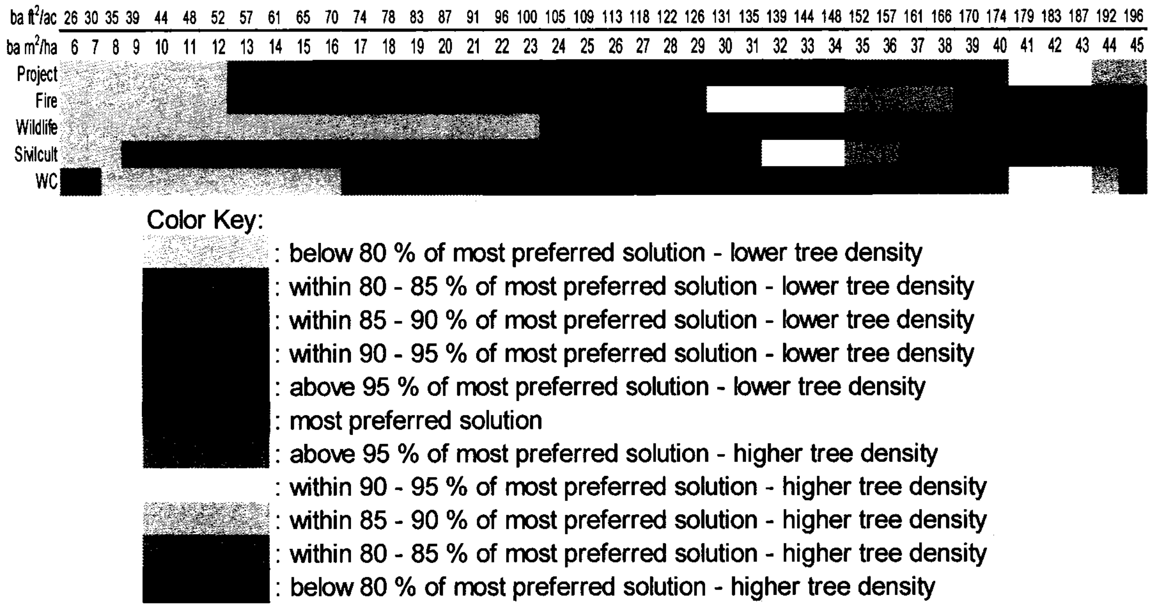

Figure 4-4: The columns represent the management alternatives, whereas each row represents a different preference structure. The most preferred solutions - in terms of management alternatives - for a given weighting scheme are colored in a dark green.

Table 4-2: Ranges of preferred basal areas with respect to all 22 management objectives under each one of the five weighting schemes.

Weighting Scheme	Preferred Basal Area in m^2/ha	Preferred Basal Area in ft^2/ac
Project	32 - 34	139 - 148
Fire	22	96
Wildlife	39	170
Silviculture	24	105
Weed/Understory	35	152

Figure 4-4 provides us with the most preferred basal area for each weighting scheme plus some additional information from Figure 4-3. Here we can clearly see the performance of the various TBA levels compared to the most preferred TBA for a given weighting scheme. While all preference structures have a narrow definition of the “most preferred basal area,” what falls within 10% below and above the best basal area varies dramatically. “Fire” and “Silviculture” weighting schemes have a narrower range of acceptable TBA, whereas the "Wildlife" weighting scheme 10% range stretches over 10 m^2/ha (or 50 ft^2/ac). The weeds control/understory trend row indicates that the lower TBA reaches back into being within 80-85% of the best possible solution.

Table 4-3: Values of the 22 forest management objectives for two different tree basal area levels determined using CP as well as their best and worst values.

Criteria	Criterion	144 ft^2/ac	96 ft^2/ac	Best	Worst
	Scale	33 m^2/ha	22 m^2/ha	Value	Value
Scenic Beauty Index	Ordinal (1-3)	2.19	2.35	2.39	1.34
Willingness-to-pay[1]	US$/Ha	53.94	65.96	67.45	0.00
Willingness-to-pay[2]	US$/Ha	14.46	17.36	17.87	0.00
Beetle Attacked Trees	% of TBA Killed	1.86	1.41	0.72	2.19
Bark Beetle Hazard Rating	Ordinal (1-12)	8	6	2.31	10.81
Dwarf Mistletoe Rating	10-yr Infection Rate	1.13	0.98	0.77	1.28
Individual exotic plants	Plants/HA	7.43	10.90	3.96	25.79
Amount of Herbage	kg/HA	92	217	1298.64	59.65
Timber Yield	m^3/Ha	123	93	143.40	29.58
Cost of Tree Removal	US$/Ha	396.36	759.96	1.35	1288.35
Crown Fuel Load	t/Ha	10.85	7.11	1.67	14.93
Heat Intensity	kJ/m^2	137	82	40.40	309.11
Crown Fire	% Crown Burned	57.91	30.52	8.57	98.38
Sedimentation (H_2O Quality)	t/Ha/yr	3.60	7.34	0.00	12.78
Streamflow	m^3/sec	7.74	10.15	17.44	6.76
Peak Flow (Flooding)	m^3/km^2	41.95	53.39	29.47	70.03
Abert Squirel Habitat	Ordinal (1-5)	2.08	1.6	2.69	1.03
MSO Habitat	Ordinal (1-5)	1.84	0.81	2.79	0.00
Mule Deer Habitat	Ordinal (1-5)	3.17	4.1	4.32	2.85
Northern Goshawk Habitat	Ordinal (1-5)	3.81	1.92	3.87	0.00
Rocky Mountain Elk Habitat	Ordinal (1-5)	3.43	3.61	4.44	2.63
Mexican Grey Wolf Habitat	Ordinal (1-5)	3.09	3.29	4.37	2.74

Given the management objective response functions and preference structure of the project manager, the CP result suggests a preferred basal area of 32/33 m^2/ha (139-144 ft^2/acre) for the project area, as shown in Figure 4-3 and Table 4-2. Table 4-3, on the

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[1] Willingness-to-pay for forest conditions based on forests as a cultural resource

[2] Willingness-to-pay for forest conditions based on forests as a recreational resource

other hand, lists the values of the 22 management objective response functions for a TBA level of 33 m^2/ha (144 ft^2/acre), as well as the best and the worst value for that management objective response function within a TBA range from 6 to 45 m^2/ha (26-196 ft^2/ac). This allows the DMs to see the value of each individual management objective that correspond to the most preferred TBA compared to all the possible values in the given range. Because the UBC data used in this study stem from a "fuel reduction" project, Table 4-3 also lists the values of the 22 management objective response functions that correspond to 22 m^2/ha (96 ft^2/acre) tree basal area, which is the preferred TBA of the "fire" preference structure, as shown in Table 4-2.

4.6.2 Spatio-Temporal Results

Sample results of the spatial-temporal analysis of the CP results are displayed in Figures 4-5 and 4-6. The figures display the CP analysis results for each individual stand in the project area through time under the preference structure assigned by the UBC project manager (Figure 4-5) and the UBC Fire manager (Figure 4-6), respectively. Forest vegetation treatments were simulated in FVS from 2006 (Figures 4-5a and 4-6a) to 2026. Because trees have the tendency to grow, stand densities generally increase after treatment. As time progresses the CP results for individual stands changes with their increasing stand density. Some stands, are cut to levels below the most preferred tree basal area and grow into that level and possibly beyond it. Figures 4-5f and 4-6f illustrate what the achievement level of the stands in the project area would be if no treatment had taken place. (These figures are based on FVS simulation without any treatment.)

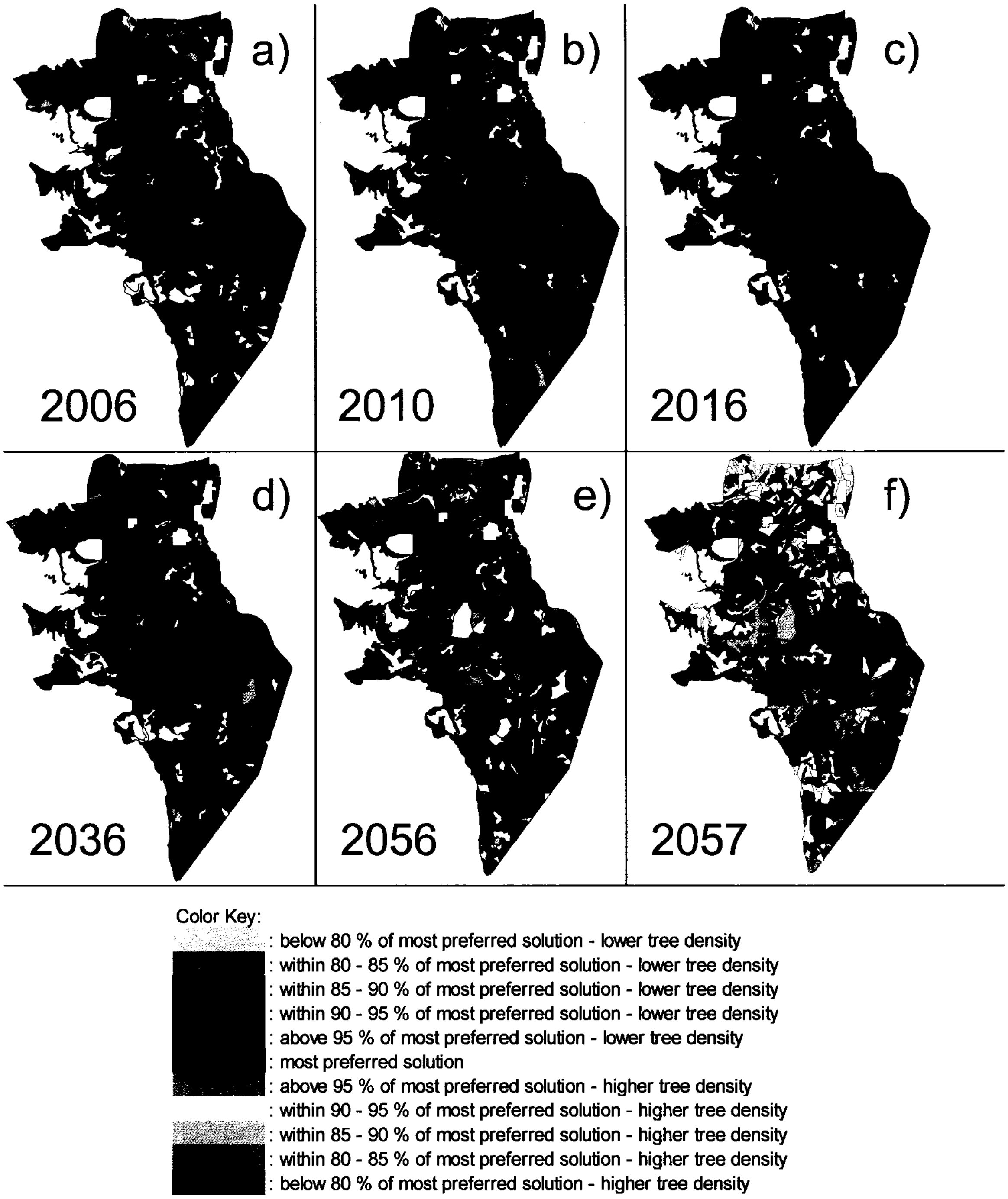

Figure 4-5: Shows how well the individual forest stands in the project area are meeting all management objectives simultaneously given the project's preference structure. a) Indicates the stands performance in 2006: The year in which the first treatment was simulated. b) – e) Indicate simulated performance at different time steps. Each figure shows how well the individual stands are meeting all management objectives simultaneously during a particular time step/project year. f) Represents the "no action alternative" and shows how the forest stands would meet all objectives if no treatment had been performed. White areas are either indicative of non-Forest Service lands or non-ponderosa pine dominated forest stands.

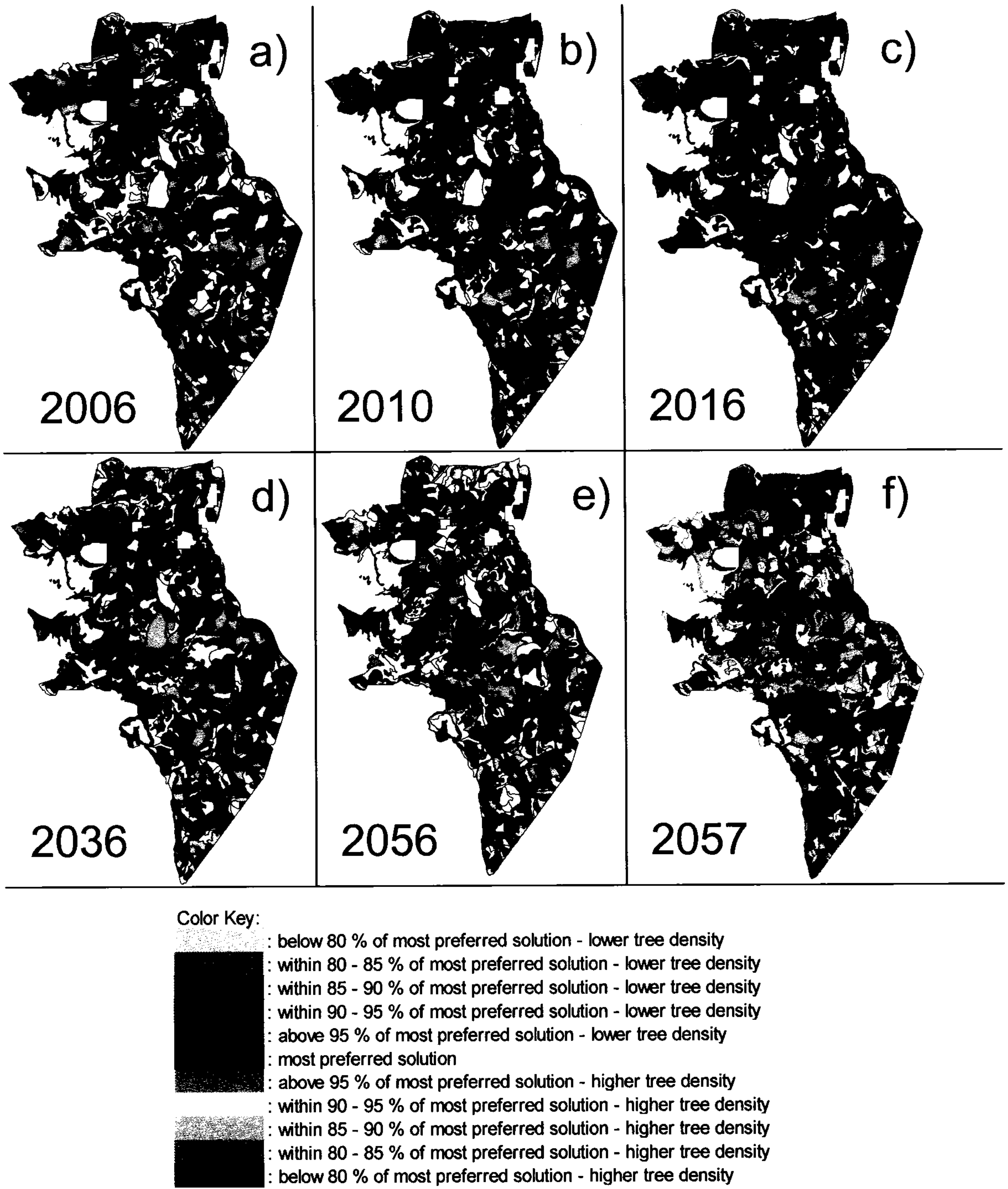

Figure 4-6: Shows how well the individual forest stands in the project area are meeting all management objectives simultaneously given the fire and fuels reduction preference structure. a) Indicates the stands performance in 2006: The year in which the first treatment was simulated. b) – e) Indicate simulated performance at different time steps. Each figure shows how well the individual stands are meeting all management objectives simultaneously during a particular time step/project year. f) Represents the "no action alternative" and shows how the forest stands would meet all objectives if no treatment had been performed. White areas are either indicative of non-Forest Service lands or non-ponderosa pine dominated forest stands.

4.7 DISCUSSION

When comparing Figures 4-5 and 4-6, one can see the differences in results between those favoring the overall project and those giving more weights to fire prevention activities. The FVS simulation projecting the forest tree growth over the next 50 years under both weighting schemes is the same. However, because the most preferred tree basal area for the project weighting scheme is much higher than that for the fire prevention (33 vs 22 m^2/ha), the treatments tend to reduce the stand density too much at first but the positive effects last much longer in the future. Given the dynamics of tree growth in a forest, it is debatable whether or not reducing a stand's density to a level that falls below the "most preferred" TBA is truly negative. With time, such a stands grows into its most preferred TBA level and remains there for a relatively long period, as illustrated in Figures 4-5 and 4-6. It appears to be much more detrimental to not achieve the most preferred level by having stands that are too dense, because they will never "grow into" the that level, unless a fire or insect outbreak reduces the live basal area within a stand. The no action alternative illustrates that the selected treatments are have a positive influence in terms of achieving all management objectives under either preference structure.

Additional information can be gathered when comparing the values of the management objective in Table 4-3 to the weights assigned to them in Table 4-1. Those objectives weighted higher, compared to the objectives weighted lower have values that are closer to the most preferred value. However, there are some management objectives that received low weights but came close to their most preferred value, as in the case of the Mexican Grey wolf habitat. Such incidences indicate that these objectives benefit from the selected most preferred TBA, even though their TBA requirements were given little consideration during the CP analysis process.

In general, the modeling effort presented in this paper is designed to help land managers, stakeholders and other decision makers concerned with southwestern ponderosa pine forest ecosystem management during their planning as well as operational phases. It is highly interactive, allowing users to evaluate different preference structures at various stages in the planning process. Different weighting schemes of the response functions can be used to reflect various preference structures of a single or a number of DMs. The advantage of this model, compared to the growth and yield models is its ability to visually display how well numerous management objectives are met simultaneously at a forest stand level, but across an entire project area or landscape. It allows DMs and land managers to see how far into the future some stands require additional treatment while other stands do not. By running multiple simulations, DMs, land managers, and stakeholders have an additional, visual tool that can be used in small team or public meeting environments, to show how various forest treatments will affect a great variety of management objectives and ecosystem components.

Some of the 22 response functions represent one ecosystem component that serves as a surrogate for another management objective. For example, the Abert Squirrel habitat response function, which is a prey for some other species, may serve as a representative those species, such as numerous bird species, that do better in denser forest stands. Even though 22 response functions are presented here, the DMs or land managers may choose to give varying importance to the different objectives. For example, a fire manager who is primarily concerned with reducing the fire hazard in the wildland urban interface may give higher weights to those response functions and objectives that reduce fire hazards at the landscape level, as the fire manager of the USFS UBC ID team did. His desired achievement levels are very different from those of the wildlife team members.

As illustrated in Figures 4-5 and 4-6 the user can see at a glance how well a selected management prescription satisfies all management objectives simultaneously on a stand by stand basis, under a selected weighting scheme. One can also easily identify the stands having too high TBA and those stands having too little and by how much (see Figure 4-5). In other words, eleven layers, one layer for each of the 11 time steps, provide mechanisms for multi-objective decision making in a spatio-temporal framework.

4.8 CONCLUSION

This paper presents an integrated model, which combines spatial and dynamic computer programs with a MODM model for evaluating multiple forest management objectives to come up with most appropriate forest ecosystem management at a landscape level. Various management objectives are addressed in a realistic and widely applicable setting. The decision variable for this model was stand density (expressed in tree basal area in m^2/ha or ft^2/ac) of the ponderosa pine forest in northern Arizona. Currently this stand density is above its historical level. The modeling scheme described in this paper is used to manage the forest to meet various ecosystem management objectives simultaneously over space and time. The tree basal area used as the decision variable links management objectives and ecosystem functions to management actions and alternatives expressed in the form of reduction of forest overstory vegetation. The outcome of CP indicates a most preferred tree basal area level of 33 m^2/ha (144 ft^2/acre) when all 22 management objectives are considered simultaneously for the project area. The “fuel reduction” weighting scheme, on the other hand suggests a TBA of 22 m^2/ha (96 ft^2/acre) tree basal area. When these different weighting schemes are evaluated in terms of their level of closeness to the most preferred alternative, the differences between the preference structures becomes even more apparent.

Future research and modeling efforts should attempt to link response functions to other forest management variables, such as stand density index (SDI) or forest structural classes. It would also be advantageous to improve the dynamic interactiveness of the spatial aspect of this modeling effort. Once this has been accomplished it would facilitate modeling the impacts of large “disturbances” such as climate change, which modelers and decision makers will have to deal with in the near future.

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CHAPTER 5 – THE UPPER BEAVER CREEK WATERSHED FUELS REDUCTION PROJECT: A CASE STUDY IN SPATIO-TEMPORAL MULTI-OBJECTIVE FOREST MANAGEMENT

Abstract: The management of forest ecosystems involves multiple interests and stakeholders with different, often conflicting expectations and management objectives. Today's changing forests require the ability to accommodate commercial as well as non-commercial objectives, both quantitative and qualitative, and respond to social, political, economic as well as cultural changes across landscapes. Models can facilitate the planning process as they are valuable tools for land managers and decision makers. One such modeling effort is used in a case study combining spatial and dynamic computer programs with a Multi-Objective Decision Making (MODM) technique. Using multiple forest management objectives, such as minimizing forest fire hazards and their effects, optimizing wildlife habitat, the author presents how such a spatio-temporal MODM technique can be used to find solutions to a dynamic forest ecosystem management problem on a landscape scale. The ponderosa pine forest in northern Arizona in general, and in the Upper Beaver Creek watershed, in particular, is currently above its historical forest stand density. Hence, forest managers can identify numerous feasible forest management alternatives in terms of reduction of the vegetation density. They can recognize to what extent the identified treatment prescriptions achieve the selected management objectives over time and space. This study takes advantage of growth and yield forest stand data and management preference structures provided by an interdisciplinary team of the USDA Forest Service Coconino National Forest. The author evaluates how well their selected prescription achieved their management goals over the next 50 years.

5.1 INTRODUCTION

The management of forest ecosystems involves many individuals or groups of stakeholders and other interests with different desires and management objectives that often conflict with each other (Bare and Mendoza 1988). Such management objectives address commodity and amenity resources that change with time and space and may be expressed quantitatively or qualitatively in the form of ordinal or cardinal data (Kennedy and Koch 2004, Thomas 2006). These objectives are applied across landscapes to changing forest ecosystems (Buongiorna and Gilles 2003). This calls for an adaptive and multi-objective management of forest ecosystems in both spatial and temporal dimensions.

Adaptive forest ecosystem management takes human interventions as experiments to learn from, and adjust to changing situations, while considering the varying needs and aspirations of different stakeholders. Further, adaptive management requires monitoring ecosystem components and modeling their relationships. Through models we attempt to mimic, in a rather simplified fashion, what happens to an ecosystem over time and space. However, unanticipated events, such as wildfires or insect outbreaks, may have unforeseen consequences. Also, changes in administration and leadership of land management agencies may require changes in management direction and goals. Changes in management directions may also be prompted by new understanding of resource characteristics and their interrelationships within the ecosystem as well as new social demands. So in order for our plans to have more than a short-term life, the plans should be updated on a regular basis. With the availability of temporal and spatial software for use in forest planning and considering the complexity and number of variables involved in ecosystem management, it is appropriate to model forest management in a spatio-temporal Multi-Objective Decision-Making (MODM) modeling framework. A model that can be used in such a framework, however, should be seen only as a tool in the greater concept of adaptive management.

In adaptive management, land managers acknowledge that the ecosystem they manage will be different in the future and are willing to deal with changing circumstances (Thomas 2006). However, it can be difficult to assess whether these changing circumstances and ecosystem differences are truly long term changes or whether projects are just set-up as laissez-faire (Sehlke 2006). Hence, it can be problematic to engage decision makers and stake holders in the adaptive management decision-making process, given that the future is abounding with uncertainty. It is essential to establish concepts and criteria for implementing scientifically credible and defensible management alternatives that can get widespread acceptance from decision makers and stakeholders. Yet, in order to achieve management goals and objectives, it is evitable that future adjustments in the course of management will be required (Thomas 2006). The modeling effort demonstrated in this study provides managers with a tool, which can be used for prediction and planning purposes. Even under the adaptive management concept, managers will only have hypotheses in which proposed management actions are expected to produce the anticipated results within anticipated ecological concepts. This is where monitoring or the assessment of the results of the proposed treatments and subsequent adjustments in the plans under the concept of adaptive management comes in (Thomas 2006). There are numerous recent examples of where these two concepts – adaptive management and monitoring – have been implemented successfully on a landscape scale, such as The Lake Tahoe Watershed (Murphy and Knopp 2000), The Sacramento-San Joaquin Bay Delta, The Florida Everglades, The Grand Canyon of the Colorado River and the Upper Mississippi River (NRC 2004.)

Forest planning exemplifies this situation even more so, because most forest lands use plans involving multiple often conflicting objectives. The goal of the forest planning process is to reach satisfactory achievement levels of the objectives. The primary motivation for this paper is the examination of a spatio-temporal MODM modeling effort as a planning tool for forest land management planning in the southwestern ponderosa pine ecosystem.

5.2 THE UPPER BEAVER CREEK WATERSHED FUEL REDUCTION PROJECT

The purpose of the Upper Beaver Creek Watershed Fuel Reduction Project is twofold: (1) to reduce the potential for stand-replacing wildfire occurrence that would threaten people, private property and natural resource values; and (2) to begin restoring fire-adapted ecosystems (USFS 2006). These actions are necessary in the face an altered fire regime due to fire suppression and management activities over the last 75 to 120 years (Covington et al. 1997). The forests in their current conditions with high fuel loads, low crown base heights and high canopy closure are prone to rapid crown fire spread and moderate to high burn severity due to dense vegetation and high levels of flammable standing live and dead and downed fuel (Fulé et al. 2001a, 2001b). Fire suppression in this fire-prone forest ecosystem has been remarkably successful in reducing the short-term probability of fire occurrences in the past. But the consequence is an accumulation of fuel over such large area that eventually produce fires of an intensity, extent, and human costs never before encountered (USDA/USDOI 2003). Such forests are also more susceptible to disturbances brought on from drought conditions (Brown et al. 2004, Crimmins and Comrie 2004, Westerling et al. 2006), insects and diseases, such as bark beetle attacks (Negrón et al. 2000) and dwarf mistletoe infestation (Conklin 2000, Geils et al. 2002).

The desired condition for the Upper Beaver Creek Watershed Fuel Reduction Project area is to have a landscape where the fire conditions are moving toward or achieving the desired fire regime that is appropriate for the vegetation type within the ecosystem. Based on professional experience a US Forest Service interdisciplinary (ID) team has determined that the desired condition for the ponderosa pine type is to retain and maintain some downed woody material plus an average basal area of about 15 - 16 m^2/ha (65-70 ft^2/ac) within the Wildland Urban Interface (WUI), and about an average of 15 - 18 (65-80 ft^2/ac) outside of the WUI. Within Mexican spotted owl (MSO) Protected Activity Centers (PACs) and Northern goshawk post fledging areas (PFAs), the average stand density would be greater where trees greater than 16 inches diameter at breast height (DBH) are present. The desired conditions may not be fully achieved immediately following completion of initial treatments due to limitations of the existing vegetative conditions and other constraints. The intent of the project is to show positive changes from the undesirable existing conditions toward the desired future conditions and show improvement in overall forest fire regime and other forest conditions. Forests thinned to remove fuel loads are unlikely to experience stand-replacing crown fires (Fule et al. 2001a, Omi and Martinson 2002)

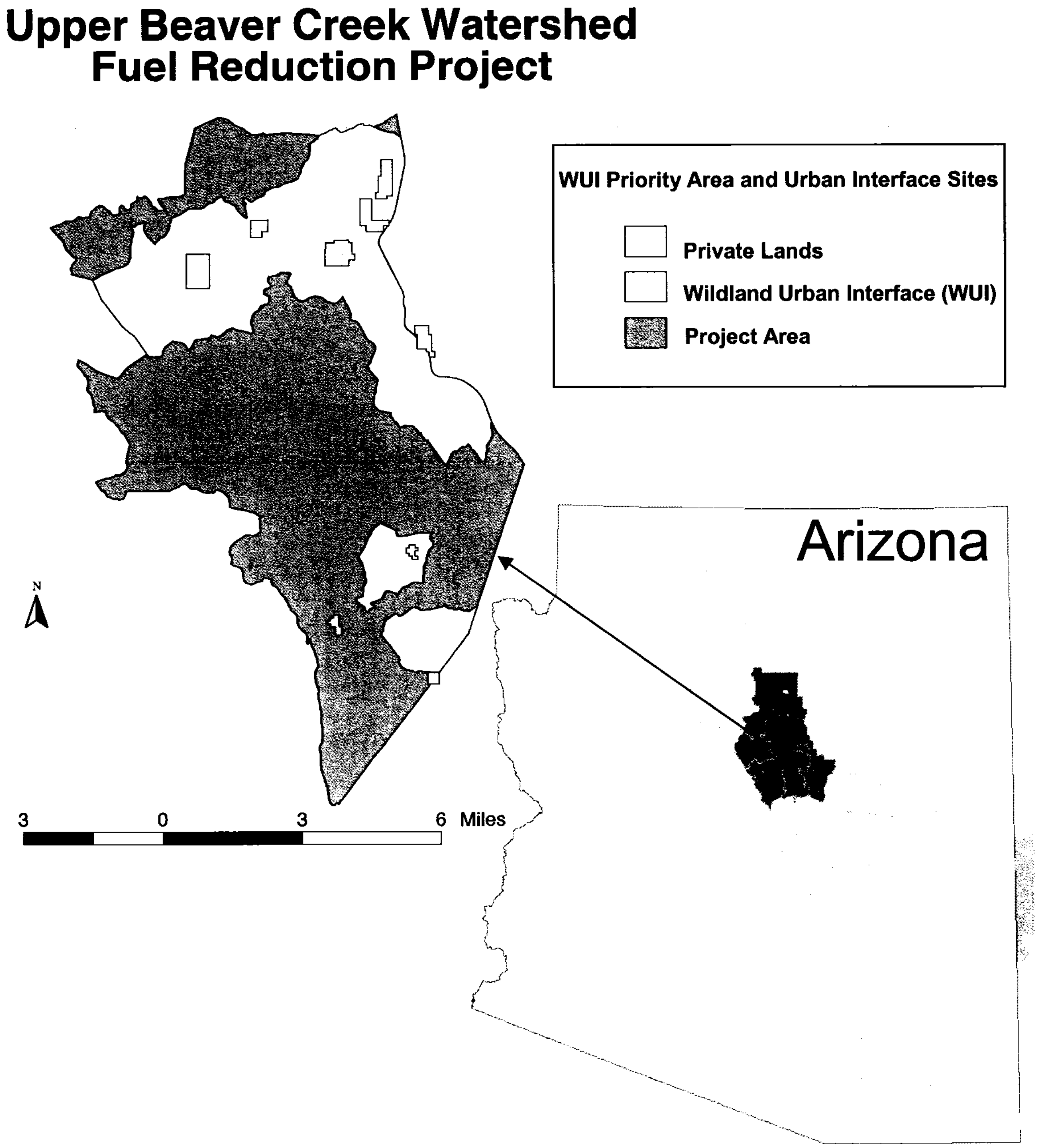

Figure 5-1: Location of the Upper Beaver Creek Watershed Fuel Reduction Project area in the Coconino National Forest (CNF) in north-central Arizona. Private lands and WUI are indicated within the project area. Other National Forests in Arizona are also shown.

5.3 METHODOLOGY

The modeling approach presented in this study consists of four components: two sets of modeling software, one MODM technique and one set of response functions.

The Forest Service's proposed actions consist of a variety of vegetation management, fuel reduction, and prescribed burning activities over the next 20 years to reduce the potential for stand-replacement wildfire and to begin restoring fire-adapted ecosystems. A detailed description of the proposed actions is given in the "Upper Beaver Creek Watershed Fuel Reduction Project: Proposed Action Report" (USFS 2006). Vegetation treatments are proposed on about 6,700 ha (18,000 acres) and prescribed burning actions are planned on about 17,700 ha (44,000 acres) within the project area. The proposed actions are designed to comply with Forest Plan standards and guidelines, as amended (USFS 1987). Design features are incorporated into the project to protect forest resources such as soil, water, air, scenic values, rare plants, wildlife and aquatic habitat. Mitigation measures are implemented to prevent the introduction and spread of invasive plants, to protect heritage resources, and to promote public health and safety during project implementation.

The Upper Beaver Creek Watershed Fuel Reduction Project (UBC) is located in north central Arizona, about 50 km (30 miles) south of Flagstaff. The project area encompasses about 19,340 ha (49,123 acres) on the Mogollon Rim and Red Rock Ranger Districts of the Coconino National Forest (Figure 5-1). The UBC area includes several developed and undeveloped private lands, and special use areas within the Wildland-Urban Interface (WUI). The designated WUI area encompasses about 6,715 ha (17,057 acres). The project area lies in the middle of the southwestern ponderosa pine forest (see Figure 5-1) and can be viewed as a good representation of the entire ponderosa pine ecosystem.

Twenty-two mathematical response functions are used individually to express each management objective. All of the objectives are described in terms of one variable – tree basal area. The MODM technique used is Compromise Programming (CP), while the Forest Vegetation Simulator (FVS) and ArcGIS are two computer programs used to describe the forest growth and yield and their variation over a landscape, respectively. FVS is an individual-tree growth model used by managers to develop land management plans. ArcGIS is a Geographic Information System, used by decision makers, land managers and analysts to create, store, analyze and manage spatial data and associated attributes. The analysis results may assist land managers of these forest ecosystems to arrive at the most preferred management actions and evaluate their achievement levels.

Advances in computer hardware and software engineering over the past few years have allowed the integration of comprehensive spatial analysis and multi-resource management modeling on a single platform with the capability for geographic data management, analysis and visualization. However, the application of dynamic system simulation, research optimization in operations and visualization of multidimensional data are still inadequate (Maguire 2005). To address this issue projected variables (tree basal area and their corresponding achievement levels) for each stand within a landscape were tied to GIS and mapped spatially so users can view the projected outcomes over time. We rely on GIS because one of the most effective ways of communication remains the visual domain. This is especially true when communicating a spatial problem to variety of conflicting stakeholders and decision-makers, particularly when the problem at hand can be represented digitally (Batty 2005). The use of GIS allows to clearly and simply represent Euclidian space in two and three dimensions.

5.4 MULTI-OBJECTIVE DECISION MAKING (MODM)

The MODM approach in this study uses Compromise Programming (CP). CP is described in detail in chapter 3 and in several pieces of literature (Poff 2002, Tecle et al. 1988, Tecle and Duckstein 1993, Zeleny 1973). It is a distance-based technique, which selects a preferred solution from a non-dominated set, on the basis of its closeness to an infeasible ideal point (Zeleny 1973). A non-dominated solution in a MODM problem is one that does not show any improvement in any one of the objective solutions without making at least one other solution worse (Tecle et al. 1988, Tecle and Duckstein 1993), while an ideal point represents the joint location of the set of maximum solutions of all the individual objectives if they were optimized separately. Therefore, arriving at a compromise solution can be viewed as minimizing a Decision Maker's (DM) regret for not obtaining the ideal solution. Weights are assigned to individual management objectives to signify the importance of one objective or criterion relative to the other objectives or criteria. Weights are assigned by the DM(s) and represent their preference structure on the objectives.

In general, all management objectives are represented by response functions, each representing a different forest ecosystem function or societal need of the forest system. The management objectives to be satisfied address some major issues for which the forest is or can be managed. Twenty-two particular objectives considered in this case study are individually described in Poff 2002 and in Appendix A. The process by which individual response functions are selected is generally external to the MODM process and is mostly dependent on the availability of data in relation to the decision variable.

The decision variable in this study consists of overstory vegetation reduction treatments and is described in the form of tree basal area (TBA) (m^2/ha or ft^2/ac). The variable has values that range from 6 through 45 m^2/ha (26-196 ft^2/ac). A TBA of 6 m^2/ha is the minimum acceptable tree density for the forest in the study area to qualify as "a forest" according to the United Nations Food and Agriculture Organization (FAO) guidelines (FAO 2006). 45 m^2/ha is the upper limit of the majority of the data available for which response functions have been created (Poff 2002). Using TBA as the decision variable has several advantages: (1) Availability of data to link management objectives and ecosystem responses to such forest density manipulation; (2) many forest-land managing agencies use TBA to quantify their management activities; (3) TBA is one of the major decision drivers and variables used in FVS, which is also utilized in this modeling effort. The disadvantage is that TBA is not sufficient to make a distinction between the conditions of some forest characteristics such as clumpiness or age distribution. However, other forest characteristics, such as trees per hectare or percent of canopy closure have an established linear relationship to TBA in the southwestern ponderosa pine forest and can easily be converted to either (Severson and Medina 1983, Rupp 1995).

The objective functions are normalized to avoid scale effects and to make all objective function values commensurable. To determine the most preferred forest management alternative in terms of its ability to achieve the desired objectives, the 22 objective response functions were first grouped into nine objective categories on the basis of their similarity in addressing related issues. For example, risk of flooding, water yield and quality are combined into the *desired hydrologic condition* category (see Table 5-1). Compromise Programming is used here to perform a two-level trade-off analysis of the ecosystem management. In the first level, a compromise solution is calculated for each of the nine objective categories, and another trade-off analysis is performed between the nine objective categories to determine the overall preferred solution.

Table 5-1: Objective Categories, Specifications, Criteria and Criterion Scales of the ponderosa pine forest ecosystem management.

Objective Categories	**Specifications**	**Criteria**	**Criterion Scale**
Maximize *Social Benefits*	Aesthetic Quality	Scenic Beauty Index	Ordinal
	Cultural Resources	Willingness-to-pay	US$/BA
	Recreational Use	Willingness-to-pay	US$/BA
Minimize *Insects & Diseases*	Roundheaded Pine Beetle Attacks	Beetle Attacked Trees	% of BA killed
	Bark Beetle	Hazard Rating	Composite Stand Hazard Values
	Dwarf Mistletoe Infection	Dwarf Mistletoe Rating	10 yr Infestation Rate
Minimize *Exotics*	Invasive Plant Reduction	Individual Exotic Plants	Plants/Ha
Maximize *Forage*	Herbage Production	Amount of Herbage	t/Ha
Maximize *Timber*	Timber Growth	Timber Yield	m^3/Ha
Minimize *Costs*	Costs	Cost of Tree Removal	US$/Ha
Minimize *Fire Hazard &Effects*	Forest Fire	Crown Fuel Load	t/Ha
		Heat Intensity	kJ/m^2
		Crown Fire	% Crown Burned
Achieve Desirable *Hydrological Condition*	Maximize Water Quality	Sediment Yield	t/ha/yr
	Maximize Water Yield	Streamflow	m^3/sec
	Minimize Flood Hazard	Peak Flow	m^3/km^2
Optimize *Wildlife Habitat*	Non-Game Species	Abert Squirrel	Ordinal
	Threatened/Endangered Species	Mexican Spotted Owl	Ordinal
	Game Species	Mule Deer	Ordinal
		Elk	Ordinal
	Forest Service Sensitive Species	Northern Goshawk	Ordinal
	Predator Species	Mexican Grey Wolf	Ordinal

5.5 APPLICATION OF THE MODM PROCESS

In this study, the members of the Mogollon Rim Ranger District Interdisciplinary (ID) Team assigned weights to the different management objectives and their criteria specified in Table 5-1. The ID Team consisted of a Team Leader and one person each from fire management, weeds control/understory vegetation, silviculture and two wildlife habitat management experts. The members of the ID team were instructed to assign two sets of weights. The first set are within category weights (WCW) (see Table 5-2, right column), which are used in the first level of the CP analysis to find a compromise solution for each objective category. If an objective category had only one objective this step is skipped. The second set of weights is assigned to show the preference structure among the objective categories (see Table 5-2, left column). These weights are used in the second level of the CP analysis to determine the overall preferred solution, in terms of TBA.

Table 5-2: Weights range from 1 to 10; 1 indicates the objective has the least weight in the decision making process; 10 indicates the objective has the maximum weight. Values given in this table represent the preference structure of the UBC.

Weight	Objective Categories	Objectives	Criteria	WCW
3	Maximize Social Benefits	Aesthetic Quality	Visual	5
		Cultural Resources	Tree Density	4
		Recreational Use	Willingness to pay	1
9	Minimize Insects & Diseases	Dwarf Mistletoe Infection	DMR	5
		Roundheaded Pine Beetle	Beetle Attacked Trees	8
		Dendroctonus Bark Beetle	Hazard Rating	8
5	Minimize Exotics	Individual Exotic Plants	Plants/ha	N/A
5	Maximize Forage	Herbage Production	Amount of Herbage	N/A
7	Maximize Timber	Timber Growth	Timber Yield	N/A
4	Minimize Costs	Costs	Cost of Thinning	N/A
10	Minimize Fire Hazard & Effects	Forest Fire	Crown Fuel Load	9
			Crown Fire	10
			Heat Intensity	5
6	Achieve Desirable Hydrological Condition	Reduce Flood Hazard	Peak Flow	3
		Increase Water Yield	Streamflow	2
		Increase Water Quality	Sedimentation	6
8	Optimize Wildlife Habitat	Non-Game Species	Abert Squirrel	7
		Game Species	Deer (spp.)	6
			Elk	1
		Predator Species	Mexican Gray Wolf	1
		Threatened/Endangered	Mexican Spotted Owl	8
		Forest Service Sensitive	Northern Goshawk	7

The weights shown in Table 5-2 represent the preference structure of the UBC project ID Team on the individual objectives (right column) and the objective categories

The weights shown in Table 5-2 represent the preference structure of the UBC project ID Team on the individual objectives (right column) and the objective categories (left column), respectively. The preferred tree basal area for the UBC project area under these conditions is 32-34 m^2/ha (139-148ft^2/ac).

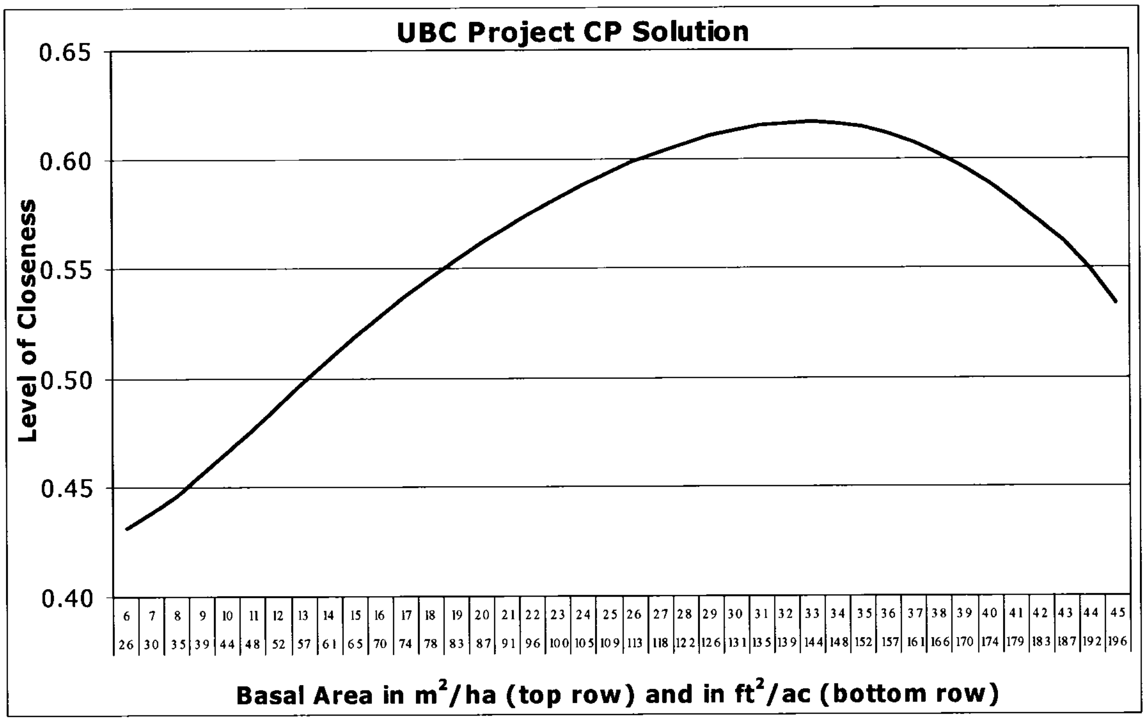

Figure 5-2: The outcome of CP for the UBC preference structures or weighting scheme display the performance of the management alternatives, expressed in basal area, for all objectives considered simultaneously.

Figure 5-2 displays the results of CP analysis of the performance of the decision variable at every 1 m^2/ha increment of its under the given preference structure. The decision variable values (in form of stand density expressed in m^2/ha and ft^2/ac basal area) serve as management alternatives and are displayed on the x-axis. The y-axis is a standardized level of closeness, which ranges from zero to one, where 1 represents an infeasible ideal point. The peak of the trend curve is the closest level to the ideal point and the decision variable value that corresponds to that point is the most preferred management level, which in this case is 32-34 m^2/ha (139-148ft^2/ac).

Figure 5-3 displays the same results in a different manner, allowing for further interpretation of the results. The columns represent the decision variable value discretizied to serve as the management alternatives (in form of stand density expressed in basal area) ranging from 6 – 45 m^2/ha (26-196 ft^2/ac), whereas the row represents the CP achievement level. The most preferred vegetation management alternatives - in terms of the decision variable values - under a given weighting scheme are colored in dark green. As the colors shift from dark green to yellow and oranges, the stand densities become increasingly too dense to satisfy all management objectives simultaneously. On the other side, as the colors shift from dark green to green, blues and purple, the stand densities decrease steadily and satisfies all management objectives less and less. Each change in color away from the dark green signifies a five percent decrease in the CP achievement level. Red and pink signify achievement levels of less than 80%, either on the increasing or decreasing trends in tree basal area, respectively. The same color coding is used later in the ArcGIS analysis.

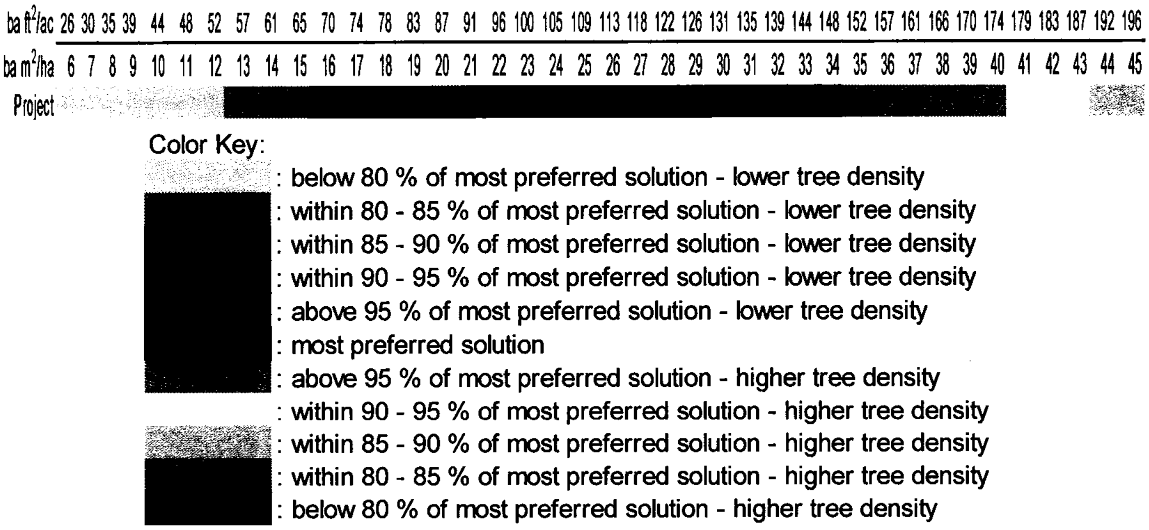

Figure 5-3: The columns represent the management alternatives, whereas the row represents the UBC preference structure. The most preferred solution - in terms of management alternatives - is colored in a dark green.

shows the basal area that falls into what percentage above or below the most preferred solution under the given weighting scheme. While the achievement level has a narrow definition of the "most preferred basal area," there is a wide spread of what falls within 10% below and above the best basal area.

5.6 FOREST VEGETATION SIMULATOR

The first modeling software applied in this spatio-temporal MODM framework is the US Forest Service's Forest Vegetation Simulator (FVS). FVS is a forest management tool for predicting forest stand dynamics. In the process FVS can summarize current stand conditions, and project future stand conditions under various management alternatives (Dixon 2002). The output from FVS can be used as input into forest planning models as well as other analysis or spatial tools such as geographic information systems (GIS) (McMahan et al. 2002). FVS is described in detail in "Essential FVS: A User's Guide to the Forest Vegetation Simulator" (Dixon 2002) and "Forest Vegetation Simulator" (USFS 2005).

In this study, the US Forest Service Mogollon Rim Ranger District ID Team provided the FVS output data for use in the modeling effort. The FVS data consisted of Microsoft Excel files, which were converted to data base files (.dbf) for use in ArcGIS. Other data provided by the ID Team included an ArcGIS shape file (.shp), which contained the polygons of all stands within the project area and the geographic links to each of the stand files provided in FVS. The forest stands in the project area represent management units of trees based on their average basal area. These stands were classified by previous management activities, which mainly consisted of logging.

Unrelated to CP, the ID Team has identified 13 different burning and nine different thinning prescriptions in the project area. FVS simulated 17, 687 ha (44,040 acres) of prescribed burning and 6,693 ha (16,665 acres) of thinning treatments over twenty years. The time scale for the simulation is 50 years with two year time steps for the first ten years and ten year time steps for the remaining forty years. Further details on the treatment descriptions can be found in the "Upper Beaver Creek Watershed Fuel Reduction Project: Proposed Action Report" (USFS 2006). Because of unpredictable factors, such as global climate change and related increased probability for wildfires and insects outbreaks, the ID Team did not deem it necessary to plan or speculate for more than 50 years into the future.

5.7 GEOGRAPHIC INFORMATION SYSTEM (GIS)

The second modeling software used in this modeling endeavor is ESRI ArcGIS. The ModelBuilder extension of ArcGIS allows the user to build a model using a diagram that resembles a flowchart (Krivoruchko and Gotway-Crawford 2005, Maidment et al. 2005, Miller et al. 2005) (see Figure 5-4). In this feature of the ArcGIS software, the model consists of a set of spatial processes that convert input data into an output layer. ModelBuilder itself is not dynamic in version 9.1, however, temporal components can be simulated by running the model multiple times, using a regular time step (Miller et al. 2005). This methodology was used in this study.

Using the query function in Modelbuilder eleven layers were created per weighting scheme per time step output given in the FVS table (see Figure 5-4). The eleven layers per weighting scheme were then grouped into one layer. This leaves one

Using the query function in Modelbuilder eleven layers were created per weighting scheme per time step output given in the FVS table (see Figure 5-4). The eleven layers per weighting scheme were then grouped into one layer. This leaves one layer per time-step, which displays the 11 sub-layers, each representing a color coded achievement level of the given weighting scheme on a stand by stand basis. Values that were outside the achievement level range displayed in Figure 5-3 were extrapolated, based on the trend curve shapes displayed in Figure 5-2, to create achievement level layers where necessary.

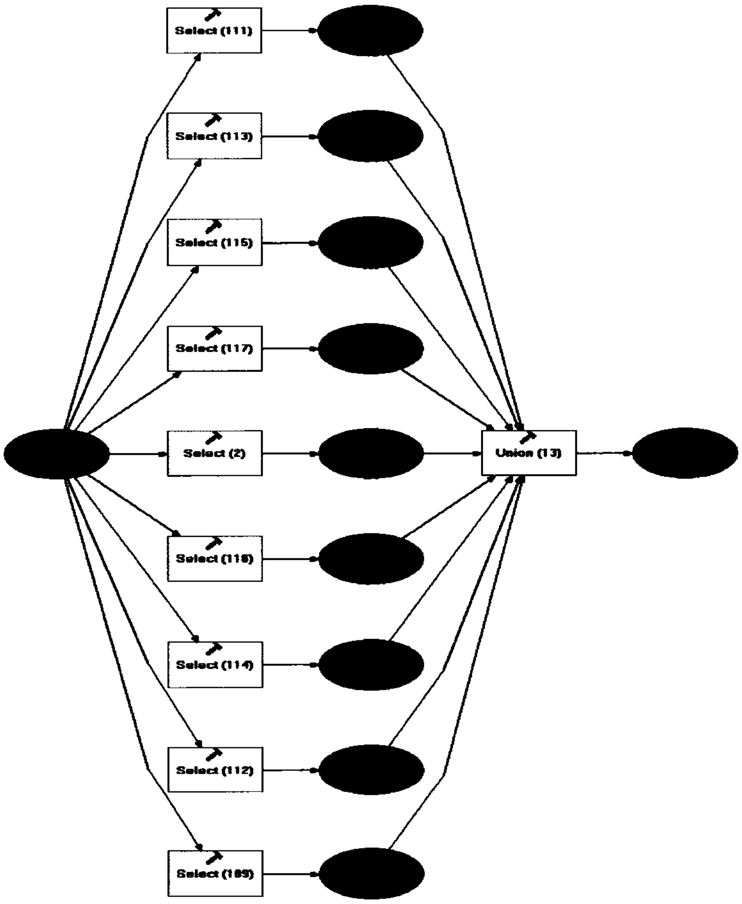

Figure 5-4: A flow chart of how ArcGIS ModelBuilder is used to create eleven output layers per time step.

simulating forest growth as if no treatment had been administered. The eleven sub-layers, for each time step, are color coded as shown in Figure 5-3. As illustrated in Figure 5-5 the user can see at one glance how well the selected management prescription satisfies all management objectives simultaneously on a stand by stand basis, given the selected weighting scheme. One can also easily see which stands have too high of a stand density and which stands have to little and by how much (see Figure 5-5). In other words, the individual stands of the project area landscape are color coded as to what percentage they fall into with relation to the CP achievement level. The eleven layers, one layer for each of the 11 time steps, provide a MODM spatio-temporal output.

5.8 RESULTS

The results of this case study modeling effort are two-fold. (1) The MODM technique arrives at a most preferred tree basal area (TBA), based on the DM's preference structure. The calculated most preferred TBA, in turn, gives us values for each of the 22 management objectives at that basal area, as listed in Table 5-3. The CP results also provide us with a level of closeness. This measure of closeness of the CP solution to the ideal point serves as a surrogate for the achievement levels of the management problem. This achievement level is an indicator to what extent all objectives are met at each TBA value. (2) The FVS forest growth and treatment simulation provides us with TBA on a stand level basis, which is then matched with a CP results in ArcGIS. This gives us a visual representation of how well all management objectives are achieved simultaneously through time for the entire landscape of the project area (see Figure 5-5).

Table 5-3: Values of the 22 forest management objectives for the most preferred tree basal area level determined using CP as well as their best and worst values.

Criteria	Criterion Scale	144 ft^2/ac 33 m^2/ha	Best Value	Worst Value
Scenic Beauty Index	Ordinal (1-3)	2.19	2.39	1.34
Willingness-to-pay[1]	US$/Ha	53.94	67.45	0.00
Willingness-to-pay[2]	US$/Ha	14.46	17.87	0.00
Beetle Attacked Trees	% of TBA Killed	1.86	0.72	2.19
Bark Beetle Hazard Rating	Ordinal (1-12)	8	2.31	10.81
Dwarf Mistletoe Rating	10-yr Infection Rate	1.13	0.77	1.28
Individual exotic plants	Plants/HA	7.43	3.96	25.79
Amount of Herbage	kg/HA	92	1298.64	59.65
Timber Yield	m^3/Ha	123	143.40	29.58
Cost of Tree Removal	US$/Ha	396.36	1.35	1288.35
Crown Fuel Load	t/Ha	10.85	1.67	14.93
Heat Intensity	kJ/m^2	137	40.40	309.11
Crown Fire	% Crown Burned	57.91	8.57	98.38
Sediment Yield (H_2O Quality)	t/Ha/yr	3.60	0.00	12.78
Streamflow	m^3/sec	7.74	17.44	6.76
Peak Flow (Flooding)	m^3/km^2	41.95	29.47	70.03
Abert Squirel Habitat	Ordinal (1-5)	2.08	2.69	1.03
MSO Habitat	Ordinal (1-5)	1.84	2.79	0.00
Mule Deer Habitat	Ordinal (1-5)	3.17	4.32	2.85
Northern Goshawk Habitat	Ordinal (1-5)	3.81	3.87	0.00
Rocky Mountain Elk Habitat	Ordinal (1-5)	3.41	4.44	2.63
Mexican Grey Wolf Habitat	Ordinal (1-5)	3.07	4.37	2.74

Given the management objective response functions and preference structure of the DMs, the CP result suggests a preferred basal area of 32-34 m^2/ha (139-148 ft^2/acre) for the project area, as shown in Figure 5-3. Table 5-3, on the other hand, lists the values of the 22 management objective response functions for a TBA level of 33 m^2/ha (144 ft^2/acre), as well as the best and the worst value for that management objective response function within a TBA range from 6 to 45 m^2/ha (26-196 ft^2/ac). This allows the DMs to see the value of each individual management objective that correspond to the most preferred TBA compared to all the possible values in the given range.

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[1] Willingness-to-pay for forest conditions based on forests as a cultural resource

[2] Willingness-to-pay for forest conditions based on forests as a recreational resource

Sample results of the spatial-temporal analysis of the CP results are displayed in Figure 5-5. The figure displays the CP analysis results of each individual stand in the project area through time. Forest vegetation treatments were simulated in FVS from 2006 (Figure 5-5a) to 2026. Because trees have the tendency to grow, stand densities generally increase after treatment. As time progresses the CP results for individual stands change with treatment followed by simulated increase in density through tree growth. Some stands, are cut to levels below the most preferred basal area and grow into that level and possibly beyond it. Figure 5-5f) illustrates the "no action" alternative or what the CP achievement level of the stands in the project area would be if no treatment had taken place. (This figure is based on FVS simulation without any treatment.)

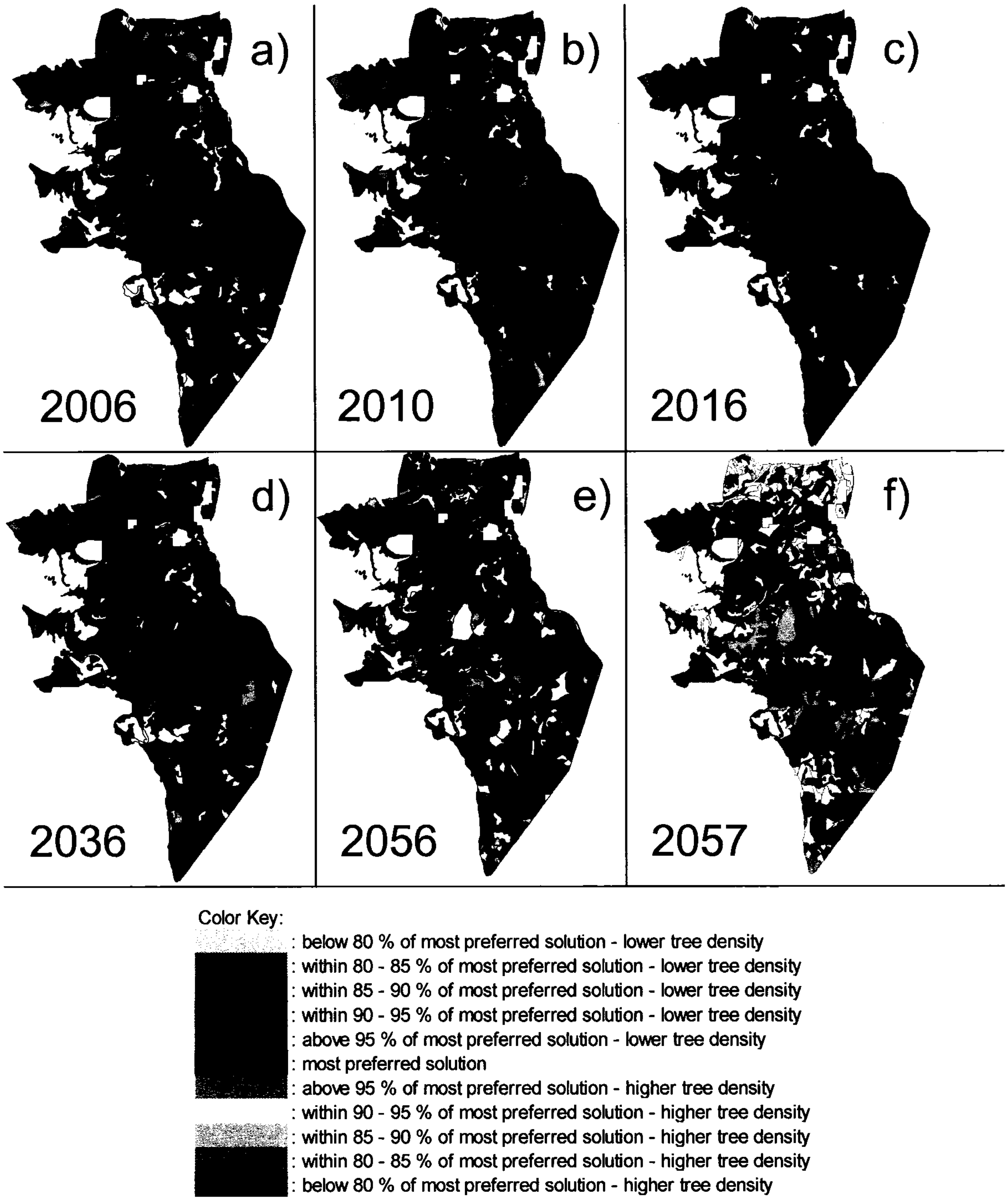

Figure 5-5: Shows how well the individual forest stands in the project area are meeting all management objectives simultaneously given the project's preference structure. a) Indicates the stands performance in 2006: The year in which the first treatment was simulated. b) – e) Indicate simulated performance at different time steps. Each figure shows how well the individual stands are meeting all management objectives simultaneously during a particular time step/project year. f) Represents the "no action alternative" and shows how the forest stands would meet all objectives if no treatment had been performed. White areas are either indicative of non-Forest Service lands or non-ponderosa pine dominated forest stands.

Using the statistical functions in the ArcGIS property tables for the individual layers is an easy method to create a variety of tables and/or graphs (i.e. Table 5-5), which allows the user to investigate various aspect of the spatio-temporal data. Figure 5-5 enables the ID team to evaluate how well the selected treatment prescription meets their objectives, given the preference structure. Table 5-4 provides a more detailed breakdown of the same information. Half way through the treatments (2016) the majority of the acreage falls below the best possible TBA. It appears to be favorable to reduce the forest to a density that is lower than the best possible solution, because stands will grow into the most preferred density and eventually grow out of it, at which time a new treatment can be scheduled. 30 years post the last treatment, 66% of the project area falls within ±5% of the best possible TBA. Only about 13% of the project area has a stand density that is too high and particularly susceptible to catastrophic wildfires, whereas without treatment 34% of the area would fall into this high risk category.

Table 5-4: The table summarizes how many hectares of the project area fall into which achievement level, depending on the time step year. 2006 is the year of the first treatments. 2016 is in the middle of the treatment and 2056 (the last year of the simulation) is 30-years post treatment. 2057 illustrates the achievement levels of the no action alternative.

Achievement Level	2006 start of tx	2016 mid tx	2056 post tx	2057 no tx
▨	1,511	3,398	1,385	356
■	781	2,111	553	120
	2,834	3,863	993	114
	1,938	2,284	1,854	89
	6,073	4,067	5,351	3,211
	1,404	1,062	2,352	1,303
	1,559	710	3,150	6,615
□	813	151	1,162	3,213
▨	166	30	354	636
■	365	8	269	1,277
	446	205	466	957

The results presented here can be used (1) to evaluate how well a selected treatment prescription achieves all management objectives simultaneously over time on the landscape for a given preference structures and (2) to aid in the decision making process which stands should be treated again and when.

5.9 DISCUSSION

The CP results for the UBC case study suggests a preferred tree basal area of 32-34 m^2/ha (139-148 ft^2/acre), which are higher than the densities given in the ID team Proposed Action Report: 15-16 m^2/ha (65-70 ft^2/ac) within the Wildland Urban Interface (WUI), and about an average of 15-18 (65-80 ft^2/ac) outside of the WUI. Apparently, a lot of weight was given to Mexican spotted owl Protected Activity Centers (PACs) and Northern goshawk post fledging areas (PFAs), where the average stand density would be greater. According to Figure 5-3 the UBC ID team desired TBA fall only into the 80-90% achievement level given the weights they assigned to all management objectives. However, the selected 20-year treatment prescription renders about half of the project landscape within ± 5% of the most preferred solution for the majority of the simulated time (50 years), given the project preference structure. This suggests that the selected treatment, even though it at first appears to be too aggressive, puts the forest on a sustainable trajectory for at least the next 50+ years. Taking into consideration the slow growth rates of southwestern ponderosa pine, the selected treatments keep the forest in a relatively steady and stable state, which, in turn, maintains the resilience of this forest ecosystem. The greatest threat to this system is a catastrophic stand replacing wildfire, as seen in other parts of the Southwest over the last decade. Such large scale disturbances can flip an ecosystem from one stable state into another, i.e. forests into grasslands. By treating the forest, as proposed in the UBC case study, a stand density can be achieved that satisfies 22 management objectives simultaneously with a 95% achievement level for about half of the project area for more than half a century.

Based on the simulation and modeling effort presented here, it would be advisable for the project area to be actively managed and treated on a continued basis, and less aggressive in some areas and more aggressive in others. This would result in reaching a 95% achievement level in more than half of the project area for 50+ years. Still, 30 years after the treatments have ceased, in 2056, only about 12% of the project area has grown denser than the most preferred stand density. Simulating the "no action alternative" shows that almost three times as much area in the UBC would be in greater risk of a stand replacing wildfire 50 years from now. Of course, 50 years from now the preference structure might have changed, wildfires or insects outbreaks may have already occurred. However, based on the knowledge and modeling capabilities we have now, the proposed action appears very reasonable.

The model presented in this paper is designed as a tool for use by land managers and other decision makers concerned with southwestern ponderosa pine forest ecosystems during their planning as well as operational phases. As such it is highly interactive, allowing the users to evaluate different preference structures and FVS simulations at various stages of the planning process. Different weighting schemes of the response functions can be used to reflect preference structures of a number of decision makers (DM), such as a Forest Service ID team. Some response functions represent one ecosystem component that serves as a surrogate for a different management objective. For example, the habitat response function of Abert squirrels, which, in turn, is considered prey by some other species, may also serves as a representative for numerous bird species that do better in denser forest stands.

Even though 22 response functions are presented here, which, in turn, are mathematical representations of management objectives, it does not mean that DMs or land managers need to or choose to give very much importance to all of the objectives. For example, a fire manager may be primarily concerned with reducing the fire hazard in the WUI, and hence gives the most weight to those response functions and objectives that reduce the fire hazard on the landscape he is responsible for.

Because CP uses straight forward computations it can easily be used in a spreadsheet, which makes it user friendly. Using FVS as the temporal projection component in this modeling effort has several advantages. Generally, the software is widely used by land managing agencies, such as the US Forest Service and is understood and trusted by DM and stakeholders (Dixon 2002). The interactiveness of the set up of the model demonstrated in this paper allows users to plug in FVS simulations created for other purposes, such as when using the software *Informs*, and receiving a spatio-temporal MODM output with very little extra effort.

The advantage of this model, compared to the growth and yield models is its ability to visually display how well numerous management objectives are met simultaneously on a forest stand basis, across an entire project area or landscape. It allows DM and land managers to see how far into the future a stand requires additional treatment and which stands do not. By running multiple simulations DM, land managers and stakeholders have an additional, visual tool that can be used in small team or public meetings, which allows them to show how various forest treatments will affect a great variety of management objectives and ecosystem components.

Today's computing power allows us to realize concepts that in previous decades had been just that: Concepts. ArcGIS Modelbuilder, for example, allows the user to combine the outputs of the MODM technique CP and the dynamic forest vegetation simulator growth modeling software FVS and display the combined results spatially. In other words, it allows us to model southwestern ponderosa pine forest ecosystem management in a spatio-temporal multi-objective decision making framework.

5.10 CONCLUSION

This paper presents an integrated model, which combines spatial and dynamic computer programs with a MODM model for evaluating multiple forest management objectives to come up with spatio-temporal solutions for a forest ecosystem management problem on a landscape scale. Various management objectives are addressed in a realistic and widely applicable setting. The x-variable for this model was the stand density (expressed in basal area m^2/ha and ft^2/ac) of the ponderosa pine forest in northern Arizona. Currently this stand density is above its historical levels. In this case study, the proposed management actions in the Upper Beaver Creek Watershed Fuel Reduction Project Area were used to evaluate the applicability of a spatio-temporal multi-objective decision-making model in a ponderosa pine forest ecosystem management framework. The model allows the users to identify how well their proposed actions meet 22 management objectives simultaneously over space and time. The modeling effort presented here has proven to be a valuable addition to the toolbox of adaptive management.

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CHAPTER 6- SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY

This dissertation presents a modeling effort, which combines spatial and dynamic computer programs with a Multi-Objective Decision-Making (MODM) technique using multiple forest management objectives to come up with spatio-temporal solutions for a forest ecosystem management problem on a landscape scale. Three papers present different aspects of this modeling effort. The first paper, which is the third chapter in this dissertation, provides a conceptual approach to modeling forest ecosystem management in a spatio-temporal MODM framework. The chapter contains the mathematical background, concepts, as well as step by step instructions of how to successfully model forest management in such a framework. The forth chapter consists of a paper that is intended to address some of the socio-political aspects of the modeling effort. The last paper or chapter five, describes the Upper Beaver Creek Fuel Reduction Project (UBC), which is used as a case study in this dissertation, and provides the results for UBC based on the inputs provided by the USFS ID team responsible for the project area.

In this modeling effort, management objectives were linked to the density of forest stands expressed in tree basal area (TBA) (expressed in m^2/ha and ft^2/ac) via mathematical response functions. The MODM technique used is Compromise Programming (CP), while the Forest Vegetation Simulator (FVS) and ArcGIS are the software programs, which describe the dynamic and spatial aspects of the forest management modeling framework.

Management actions, such as thinning and prescribed burning, in ponderosa pine ecosystem were used to evaluate the applicability of a spatio-temporal MODM modeling effort in a forest management framework. The decision variable for this model was the tree basal area of the ponderosa pine forest in northern Arizona, where the current stand densities are above historical levels. In order to be meaningful to managers, the decision variable must be susceptible to alteration by management actions. Using TBA as the decision variable has several advantages: (1) Availability of data relating management objective or ecosystem functions to TBA in constructing response functions; (2) many government agencies use TBA to quantify their management activities; (3) TBA is one of the major decision drivers and variables used in FVS. The disadvantage is that TBA is not sufficient to make a distinction between the conditions of some forest characteristics such as clumpiness or age distribution. However, other forest characteristics, such as trees per hectare or percent of canopy closure have an established linear relationship to TBA in the southwestern ponderosa pine forest and can easily be converted to either.

The demonstrated modeling effort provides results at three stages: (1) the MODM stage; (2) the temporal projection stage; and (3) the spatial projection (GIS) stage. Even though the user of this modeling effort is ultimately interested in the output at the last stage, the interactiveness of this process allows the modelers/DMs to make modifications at either of the first two stages: the MODM stage and the temporal projection stage.

6.2 CONCLUSIONS

In general, the presented modeling effort presented is designed as a tool for use by land managers, stakeholders and other decision makers concerned with southwestern ponderosa pine forest ecosystems during their planning as well as operational phases. It is highly interactive, allowing the users to evaluate different preference structures at various stages of the planning process. The weights represent the preference structures between the various response functions of a single or a number of DMs. The advantage of this model, compared to the growth and yield models is its ability to visually display how well numerous management objectives are met simultaneously on a forest stand basis, across an entire project area or landscape. It allows DMs and land managers to see how far into the future a stand requires additional treatment and which stands do not. By running multiple simulations, DMs, land managers, and stakeholders of the ponderosa pine forest ecosystems in northern Arizona have an additional, visual tool that can be used in small team or public meetings, which allows them to show how various forest treatments will affect a great variety of management objectives and ecosystem components. Further, it allows for the demonstration of how resilient the forest ecosystem is in response to varying levels of management actions.

In a case study, the proposed management actions in the Upper Beaver Creek Watershed Fuel Reduction Project Area (UBC) were used to evaluate the applicability of a spatio-temporal MODM modeling effort in a ponderosa pine forest ecosystem management framework. The model allowed the UBC USFS ID team to identify how well their proposed actions meet 22 management objectives simultaneously over space and time. The modeling effort presented here has proven to be a valuable addition to the toolbox of adaptive management.

A modeling effort, as the one suggested in this dissertation, is objective, transparent and therefore defensible in legal and social settings. The MODM technique in itself is objective, because it converts the management objectives, both quantitative and qualitative, into mathematical response functions, which have no emotional values attached to them. Transparency is achieved by disclosing the decision makers' preference structure in form of the weights that are assigned to the various management objectives in the given project area. Weights signify the importance of one objective relative to another objective. This transparency allows member of the affected communities to see how the experts arrive at their decisions, by externalizing this otherwise internal process.

6.3 RECOMMENDATIONS

Future research and modeling efforts should attempt to link response functions to other forest variables, which management actions can alter, such as forest structural classes and stand density index (SDI) may be interesting. SDI in particular will be easy to use from a research and from a practioner's stand point because SDI is comprised of tree basal area, trees per area and a selection of tree sizes. The response functions used herein are particular to southwestern ponderosa pine ecosystem. In order for this modeling effort to have applicability in other parts of the country, it would be useful to develop local response functions for forest and woodland ecosystems throughout the continent. One possible improvement in this modeling effort is to develop it into a post processor of FVS. As such it would likely be used by forest management practioners. Once this has been accomplished it would facilitate modeling the impacts of large "disturbances" such as climate change, which modelers and decision makers will have to deal with in the near future.

Appendix A: Summary of Response Functions

Objectives	Based on	Mathematical formulations of management objectives	r^2 values
Social Concerns			
>Aesthetic Value	Brown et al. (1974); Tecle et al. (1998)	$Z_1 = 1.144-0.001974(x/0.2296)+0.004718(x/0.2296)^2-0.000004356(x/0.2296)^3+0.00000001059(x/0.2296)^4$	N/A
>Cultural Resources	Loomis (1996)	$Z_2 = -59.334+10.221x-0.206x^2$	0.98
>Recreation	Loomis (1996)	$Z_3 = -16.03+2.706x-0.054x^2$ Where Z_1 = Scenic Beauty Estimator Index (SBE) Z_2 = Willingness-to-pay for forest preservation at given ba/ha Z_3 = Willingness-to-pay for recreational experience in given basal area/ha x = Tree basal area m^2/ha	0.96
Insects and Diseases			
>Roundheaded Pine Beetle	Negrón et al. (2000)	$Z_4 = 0.453+0.044x-0.000025x^2-0.0000021x^3$	0.88
>*Dendroctonus* Bark Beetle	McMillain (2006)	$Z_5 = 1+0.218x+0.0000000000000231x^2-0.0000000000000000033x^3$	1
>Dwarf Mistletoe Intensification Rate	Geils and Mathiasen (1990)	$Z_6 = 0.697+0.013x-0.0000007x^2$ Where Z_4 = Percent ponderosa pine basal area killed from roundheaded pine beetle Z_5 = Composite Stand Hazard Values from bark beetle infestation Z_6 = 10-Year Dwarf Mistletoe Infestation Rate/ha x = Tree basal area m^2/ha	N/A
Minimize Exotic Species	USFS Data, Coconino NF (1999)	$Z_7 = 36.57-2.097x+0.053x^2-0.0005x^3$ Where Z_7 = Number of Scotch thistles observations/ha x = Tree basal area m^2/ha	0.55
Maximize Herbage Production	Covington & Fox (1991) Tecle et al. (1998)	$Z_8 = \{(45+24a/25.4+55d)(exp(-0.0289(x/0.23))\}*1.1208$ Where Z_8 = herbage production a = annual precipitation (= 762 mm average for study area) d = depth of soil to impedance layer (cm) (= 30 cm average for study area) x = Tree basal area m^2/ha	N/A
Maximize Timber Production	Ronco et al. (1985), Tecle et al. (1998)	$Z_9 = 17.06(x/0.2296)-0.03369(x/0.2296)^2*0.06997$ Where Z_9 = merchantable timber growth volume in m3/ha x = Tree basal area m^2/ha	N/A
Minimize Operational Costs	Turner and Larson (1974)	$Z_{10} = 1486.35-33x$ Where Z_{10} = Cost of Thinning to desired basal area expressed in 2000 US\$ x = Tree basal area m^2/ha	N/A

Minimize Fire Hazard & Effects			
>Fire Hazard	Fulé et al. (2001a, 2001b)	$Z_{11} = -0.37+0.34x$	0.96
>Heat Generated		$Z_{12} = 1.763+8.54x-0.398x^2+0.008x^3$	0.75
>Size of Fire		$Z_{13} = 5.818+0.212x+0.041x^2$	0.52
		Where Z_{11} = Crown Fuel Load (t/ha) Z_{12} = Heat Generated (kJ/m^2) Z_{13} = Percent of Crown Burned (%) x = Tree basal area m^2/ha	
Hydrological Concerns			
>Water Quality	Brown et al. (1974)	$Z_{14} = 14.82-0.34x$	N/A
>Water Yield	Rogers et al. (1984); Tecle (1991) et al. (1998)	$Z_{15} = 1.19\{-5.72+0.83Pw/25.4+42r-0.24r(Pw/25.4)^{0.92}-0.007Pw^2(1-\exp[-(x/0.23)/45)]^3\}-0.47$	N/A
>Flood hazard	Brown et al. (1974); Ffolliott and Thorud (1975); USDA Forest Service (1977); Tecle (1988, 1991)	$Z_{16} = 76.27-1.04x$	N/A
		Where Z_{14} = Sediment yield in t/ha Z_{15} = annual streamflow in cfs Z_{16} = m^2/km^2 of water flow Pw = winter (1 Oct. –30 April) precipitation (= 610 mm average for study area) R = insolation index (= 1.9 INI for study area) x = Tree basal area m^2/ha	
Wildlife Habitat Condition			
>Abert Squirrel	Patton (1984); McTague (1991) Tecle et al. (1998)	$Z_{17} = 0.857+0.02713x+0.0003027x^2$	N/A
>Mexican Spotted Owl	Ganey (1988)	$Z_{18} = 0.056-0.033x+0.0044x^2-0.00005x^3$	0.47
>Mule Deer	Wallmo and Schoen (1981); Leckenby et al. (1982); Severson and Medina (1983)	$Z_{19} = 1.659+0.386x-0.017x^2+0.0002x^3$	0.74
>Northern Goshawk	Reynolds et al. (1992), Block et al. (1994)	$Z_{20} = 0.459-0.295x+0.025x^2-0.0004x^3$	0.86
>Elk	Severson and Medina (1983); USDA Forest Service (2002)	$Z_{21} = 2.5572+0.3178x-0.0159x^2+0.0002x^3$	0.7
>Mexican Gray Wolf	Allen (1990); Johnson (1990); Jedrejewska et al. (1994)	$Z_{22} = 2.108+0.3518x-0.0164x^2+0.0002x^3$	0.66
		Where Z_{17} =Abert Squirrel Habitat Index Z_{18} = Mexican Spotted Owl Habitat Index Z_{19} = Mule Deer Habitat Index Z_{20} = Northern Goshawk Habitat Index Z_{21} = Rocky Mountain Elk Habitat Index Z_{22} = Mexican Grey Wolf Habitat Index x = Tree basal area m^2/ha	

N/A: r^2 value is not available because the original response function has been developed by respective authors and value was not given.

APPENDIX A: LITERATURE CITED

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