ADDRESSING CLIMATE CHANGE UNCERTAINTY IN FOREST PLANNING:
A MULTI-STAGE OPTIMIZATION MODEL
WITH MULTIPLE FUTURES AND PRICE SENSITIVE DEMANDS

A DISSERTATION
SUBMITTED TO THE FACULTY OF THE
UNIVERSITY OF MINNESOTA
BY
IRENE DE PELLEGRIN LLORENTE

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Dr. Howard M. Hoganson
Dr. Marcella Windmuller-Campione

DECEMBER 2020
ACKNOWLEDGEMENTS

Thank you to my advisors, Dr. Howard Hoganson and Dr. Marcella Windmuller-Campione, for many hours of conversation, guidance, and patience. I learned so much from you. Thank you for the challenging times that made me grow.

I also want to express my gratitude to the Department of Forest Resources at the University of Minnesota and Dr. Mike Kilgore, for your constant support during this time. I owe a great debt to many of the professors in the Forest Resources and the Applied Economics departments for many fructiferous conversations. A special acknowledgment to the members of my committee: Dr. Chris Edgar and Dr. Frances Homans.

A special thanks to my office mates in GH330A (Brian Anderson, Justin Meier, Stephanie Patton, and Ryan Toot). My first two years in Minnesota were much easier thanks to you. I hope that our careers bring us together some time in the future. Thank you also to Michael Carson.

I wish also to express my gratitude to Alex Sierra. Thank you for your patience, support, understanding, and respect. Thank you for having always pushed me to achieve the goals that several years ago seemed unattainable.

Lastly and most important, thank you to my parents, Dante and Mercedes, for the innumerable sacrifices you made that allowed me to have an education. Thank you for always supporting my decisions and encouraging me to achieve my dreams.
A mi madre, Mercedes.
ABSTRACT

Forest ecosystems are complex, supplying numerous ecosystem services. Multiple ecological, economic, social, and political facets influence forest-planning decisions. Decision models have been widely used in forest management planning, but most are deterministic models, assuming the future is known. However, uncertainty about the future is often a concern because of long planning horizons, multiple stakeholders with different objectives, and many complexities of biological systems involving mixed-species stands and critical habitat for wildlife species. Addressing uncertainties surrounding the impacts of climate change on forests is considered a major challenge in forest planning. This research develops a stochastic forest planning model to recognize uncertainty surrounding the growth and yield estimates, allowing estimates of future growth and yield to depend on how climate changes. The intent is to help identify forest management actions for today that will perform well over a range of plausible climate change scenarios (futures). The stages of the model address how uncertainty about the future might unfold, with model solutions providing proposed immediate management actions plus detailed contingency (recourse) plans for each future. The use of specialized decomposition methods of operations research has allowed for testing the model using a very detailed statewide application in Minnesota, USA. For this case study, results show that planning for an average deterministic case produces a misleading solution, under-estimating the potential impact of climate change. On the other hand, planning for a worst-case scenario results in unsustainable harvest levels or unrealistic prices for timber in the long term. Test cases were also expanded to consider the use of downward sloping demand curves, recognizing that the marginal value of timber products and forest conditions vary with production level. Several demand curves are used and compared for aspen timber and hardwood old forest. Results demonstrate the potential for downward-sloping demand curves to help mitigate the infeasibilities and fluctuations in the marginal cost of production (shadow price) produced under the test cases with a fixed production target. Overall, these findings
advance our understanding on the implications of including forest-wide uncertainty in the forest management process and highlights important tradeoffs when considering management options in a real-world application.
Table of Contents

List of Tables .................................................................................................................................................. viii
List of Figures .................................................................................................................................................. ix

**Chapter 1: Introduction** .............................................................................................................................. 1

**Chapter 2: Integrating Ecological and Economic Objectives across the Minnesota Landscape** .................................................................................................................................................. 4

2.1 Introduction.............................................................................................................................................. 4

2.2. Materials and Methods.......................................................................................................................... 8
  a) Dualplan: background and overview of the model .................................................................................... 9
  b) Old forest and its marginal value ............................................................................................................. 12
  c) Application in northern Minnesota ........................................................................................................ 14

2.3. Results.................................................................................................................................................... 21
  a) The joint production of old forest and timber across different aspen harvest levels ......................... 22
  b) Horizontal marginal functions for old forest (fixed and constant price) ............................................. 24
  c) Vertical marginal functions for old forest (fixed and constant quantity of old forest) ............. 27
  d) Downward-sloping marginal functions ................................................................................................ 29
  e) Premiums levels for old forest by ownerships and age ....................................................................... 33

2.4. Discussion.............................................................................................................................................. 36
  a) Benefits of using downward-sloping marginal value curves ................................................................. 36
  b) Importance of forest-level analysis across forest cover types ............................................................ 37
  c) Benefits of Analysis Across Ownerships ................................................................................................ 37
  d) Additional details, data needs, and further analysis ............................................................................. 38

2.5. Conclusions........................................................................................................................................... 39

**Chapter 3: Recognizing Uncertainty in Forest Planning: Addressing Growth Uncertainty Surrounding Climate Change Using a Decomposition Model for Large Landscapes** .................................................................................................................................................. 41

3.1. Introduction........................................................................................................................................... 41

3.2. Methods................................................................................................................................................. 44
  a) Forest-Wide Uncertainty ...................................................................................................................... 44
  b) Uncertainty in Stand-level Decision Trees ......................................................................................... 45
  c) The Forest-Level Deterministic Model: DTran ................................................................................... 47
d) Integration of Uncertain Futures into the Forest-Level Model

3.3. The Test Cases

   a) Scenario Trees: Impact of the Timing and Number of Stages and Branches
   b) The Minnesota Situation

3.4. Results

   a) Comparison among Deterministic Approaches
   b) Uncertainty and Aspen Harvest Level Constraints
   c) Acres of Aspen Harvested and Acres of Old Aspen (> 80 years old)

3.5. Discussion

   a) Benefits of Considering Uncertainty versus a Deterministic Forest Planning Model
   b) Benefits of Using One Uncertainty Tree over another One
   c) Harvest Levels: Are Even Flow Constraints Suitable for Uncertainty?
   d) Considering Additional Assumptions, Data Needs, Additional Sources of Uncertainty and Further Analysis

3.6. Conclusions

Chapter 4: Integrating Climate Change Uncertainties with Price-Sensitive Timber Demands for Developing More Resilient Landscape Management Plans

4.1 Introduction

4.2 Methods

   a) Demand Curve Scenarios for Aspen Volume Constraints
   b) Additional Test Cases

4.3 Results

   a) All Species Volume Constraints
   b) Aspen Harvest Level Constraints
   c) Acres of Aspen Harvested and Acres of Old Aspen
   d) Additional Test Cases

4.4 Discussion

   a) Impacts of using a specific demand curve on aspen volume
   b) Limit on Aspen Volume
   c) Growth and Yield Multipliers: Sensitivity Analysis

4.5 Conclusions
List of Tables

Table 2.1 Percentage of the area of aspen and birch forest cover types that meet old forest requirements in each ecoregion and each stand age class. .............................................. 19

Table 2.2 Premiums considered for old forest for the low and high marginal value function scenarios for old forest of upland hardwoods based on forest cover type and stand age class ($/ha/year). ..................................................................................................................... 20

Table 2.3 Comparison of model results for nine scenarios in terms of the impact of premiums used for old forest based on ownership, forest cover type and stand age. ....... 35

Table 3.1 Acre of aspen older than 80 years at the end of period 20. ................................. 67
List of Figures

Figure 2. 1 Potential facet of forest management situations (from (Hoganson and Meyer 2015)) .................................................................................................................................................. 5

Figure 2. 2 Downward–sloping marginal value functions used for the old forest as the ecosystem service .................................................................................................................................................. 13

Figure 2. 3 Ecological regions in Minnesota. For the purpose of this study, small ecological regions were combined with a nearby section. Specifically, 212J was merged with 212K, and 251A and 251B were combined with 222M. ............................. 16

Figure 2. 4 Current age-class distribution of aspen (a), oak (b), northern hardwoods (c), and paper birch (d) cover types at the beginning of the planning horizon (period 0) in the study area ............................................................................................................................................... 21

Figure 2. 5 Amount of old forest produced under three aspen harvest levels and the high marginal value function for old forest (a) and aspen shadow prices for the three aspen harvest levels and the high marginal value function for old forest (b). ........................................ 23

Figure 2. 6 Shadow prices estimates for the all-species volume constraints across all three aspen harvest levels (low, medium, and high). ......................................................................................................................... 24

Figure 2. 7 Amount of old forest produced under the horizontal marginal functions (a) and marginal values associated with the aspen volume constraints (b). ................................. 25

Figure 2. 8 Shadow prices estimates for the all-species volume constraints across all the four fixed marginal value scenarios .................................................................................................................. 27

Figure 2. 9 Marginal value estimates for old forest under three fixed old forest target levels (a) and marginal values associated with the aspen species volume constraints with these old forest target levels (b). .................................................................................................................. 28
Figure 2. 10 Old forest flow (million hectares) (a) and their marginal value estimates for
old forest under the three marginal value functions ($/ha/year) (b). ........................................ 30

Figure 2. 11 Marginal value estimates for old forest under the three marginal value
functions (a) and marginal values for the aspen species volume constraints across
marginal value functions (b). ........................................................................................................ 31

Figure 2. 12 Northern hardwoods age-class distribution under the lowest old forest
marginal value function at year 40 (a), 60 (b), 80 (c), and 100 (d) of the 100-year
planning horizon. .......................................................................................................................... 32

Figure 2. 13 Northern hardwoods age-class distribution under the highest old forest
marginal value function at year 40 (a), 60 (b), 80 (c), and 100 (d) of the 100-year
planning horizon. .......................................................................................................................... 33

Figure 3. 1 An example of a scenario tree used to define the realization of the forest-wide
uncertainty over time. The horizontal axis measures the planning periods .................. 45

Figure 3. 2 A portion of a stand-level decision tree with forest-level uncertainty (chance
nodes) included. The numbers in each square node represent the corresponding state
within the stage. The shaded nodes represent the bare land condition that follows
immediately after harvest .............................................................................................................. 46

Figure 3. 3 The algorithm used to solve the stochastic forest planning model for the test
cases ............................................................................................................................................... 49

Figure 3. 4 Scenario trees with eight futures at the end of the planning horizon, (a) the
“(2x2x2) early” test case, (b) the “(2x2x2) late” test case, and (c) the “(4x2)” test case.
The first node, the empty dot, represents time 0. Each planning period represents 5 years.
...................................................................................................................................................... 51

Figure 3. 5 Scenario trees with 16 scenarios at the end of the planning horizon, (a) the
“(4x4)” case, and (b) the “(4x2x2)” test case. The first node, the empty dot, represents
time 0. Each planning period represents 5 years ........................................................................ 52
Figure 3.6 Description of how the yield multipliers of each stage and state of the specific test case “(2x2x2) early” are calculated. The X-axis represents time periods and the Y-axis represents a yield multiplier. The yield multipliers vary by product type, stand age, and ecological region.

Figure 3.7 Shadow prices ($/cord) by period for the timber harvest volume constraints of all the species for the three deterministic cases.

Figure 3.8 Shadow prices ($/cord) by period for the aspen harvest volume constraints for the three deterministic scenarios.

Figure 3.9 Acres of aspen older than 80 years at the end of each planning period for each deterministic test case.

Figure 3.10 Volume of aspen harvested (Cords) in the “(4x2)” case (Legend: see numbering of the different scenarios in Figure 3.4 and Figure 3.5).

Figure 3.11 Shadow prices ($/cord) associated with the aspen constraints across the eight scenarios for the “(2x2x2) early” case.

Figure 3.12 Shadow prices ($/cord) associated with the aspen constraints across the eight scenarios for the “(2x2x2) late” test case.

Figure 3.13 Shadow prices ($/cord) associated with the aspen constraints across the eight scenarios for the “(4x2)” test case.

Figure 3.14 Shadow prices ($/cord) associated with the aspen constraints across the 16 possible scenarios for the “(4x2x2)” test case.

Figure 3.15 Acres of aspen forest cover type harvest by period under each possible future scenario.
Figure 3. 16 Acres of aspen older than 80 years old left at the end of each planning period across the eight scenarios for the “(2x2x2) late” test case.......................................................... 67
Figure 3. 17 Acres of aspen older than 80 years old left at the end of each planning period across the 16 scenarios for the “(4x2x2)” test case.......................................................... 68

Figure 4. 1 Forest-wide uncertainty scenario tree used in all the test cases in this chapter. It is the “(2x2x2) early” test case in Chapter 3 .......................................................... 77

Figure 4. 2 Downward-sloping demand curves a) “Demand Curve 1”, and b) “Demand Curve 2” .......................................................................................................................... 78

Figure 4. 3 Volume of timber harvested of all the species by period, under (a) a horizontal demand curve, (b) the downward sloping demand curve 1, and (c) under the downward sloping demand curve 2 (Legend: see numbering of the different scenarios in Figure 4.1) .......................................................................................................................... 81

Figure 4. 4 Volume of aspen harvested by period (three graphs on the left column) under (a) a horizontal demand curve, (b) the downward sloping demand curve 1, and (c) under the downward sloping demand curve 2. Aspen shadow prices ($/cord) associated with the aspen volume constraint (three graphs on the right column) under (d) a horizontal demand curve, (e) the downward sloping demand curve 1, and (f) under the downward sloping demand curve 2 (Legend: see numbering of the different scenarios in Figure 4.1) .......................................................................................................................... 82

Figure 4. 5 Acres of aspen harvested by period under (a) a horizontal demand curve, (b) the downward sloping demand curve 1, and (c) the downward sloping demand curve 2 test cases. The three graphs have the same scale in both axes for comparison purposes. (Legend: see numbering of the different scenarios in Figure 4.1) ............................................. 86

Figure 4. 6 Acres of old aspen (> 80 years old) by period (three graphs on the left column) under (a) a horizontal demand curve, (b) the downward sloping demand curve 1,
and (c) the downward sloping demand curve 2 test cases. Acres of aspen between 55 and 80 years old (three graphs on the right column) under (d) a horizontal demand curve, (e) the downward sloping demand curve 1, and (f) the downward sloping demand curve 2 test cases. The three graphs on the same column have the same scale in both axes for comparison purposes. (Legend: see numbering of the different scenarios in Figure 4.1) 88

Figure 4. 7 Volume of aspen harvested by period (two graphs on the left column) under (a) a horizontal demand curve and (b) the downward sloping demand curve 1. Aspen shadow prices ($/cord) associated with the aspen volume constraint (two graphs on the right column) under (c) a horizontal demand curve and (d) the downward sloping demand curve 1 (Legend: see numbering of the different scenarios in Figure 4.1) 91

Figure 4. 8 Volume of aspen harvested by period (two graphs on the left column) under (a) a horizontal demand curve and (b) the downward sloping demand curve 1 using the new set of yield multipliers. Aspen shadow prices ($/cord) associated with the aspen volume constraints (two graphs on the right column) under (c) a horizontal demand curve and (d) the downward sloping demand curve 1 (Legend: see numbering of the different scenarios in Figure 4.1) 94
Chapter 1: Introduction

Forest managers today face new challenges that differ from the traditional ones. In the past, forest management problems focused mainly on timber resources or the sustainability of just one service. Today, the complexity of the forest management problems has increased and the scope of the services and products that people require from them has become much broader. Forest managers face difficult decisions, where the focus is on the multiple uses of the ecosystem and the interconnections of all the services provided by forest ecosystems. Today, challenges like conserving biodiversity, recreational values, or nontimber products could be as important as providing timber products. The approach of multiple uses of the land was traditionally achieved by providing one service on one stand and another service on another stand. Today, the attention is towards the interaction among goals and across individual stands to include additional outputs besides timber.

Forest planning usually deals with very complex situations where different management decisions at various scales must be satisfied. Broad landscape or forest level objectives such as timber production must incorporate very concrete stand-level details such as accessibility or stand age. All that information is necessary in order to help decision-makers define the conditions and details of the problem. The identification of alternative solutions to the problem will help forest managers decide how and when the management of the forest will best satisfy their goals, and which form and timing will be optimum to achieve them. It is crucial to evaluate and to acknowledge tradeoffs associated with the alternative management decisions or among competing objectives to inform the decision process. Decisions made in forest management usually have long-term consequences which can lead to undesired impacts on the ecosystem for a long period of time.

Mathematical programming and optimization techniques have been a particularly useful tool to help solve forest planning problems. Some of the earliest operations research applications to forest resource problems occurred since at least the 1960s. Early forest management planning models were usually formulated as linear programming (LP)
problems. Linear programming (LP) is the most widely solution technique used in solving forestry problems. Some of the first applications were mainly focused on forest regulation, and sustainable timber yields (Loucks 1964; Kidd et al. 1966; Nautiyal and Pearse 1967). Later models such as FORPLAN (Johnson and Stuart 1987) and SPECTRUM (1995) had an emphasis on land allocation, multiple-use, and environmental considerations.

However, some alternative solutions methods have also been developed in forest management planning problems. Walker (1976) developed an EConomic Harvest Optimization (ECHO) model that uses a binary search method subject to a downward-sloping demand curve. The concept of using a downward sloping demand curve, as a constraint of a forest output or condition has been limited explored in forest management planning problems. It is very interesting when used for addressing an environmental condition because it places a higher price when the condition is scarce (Chapter 2), but also when constraining timber market flows because it helps recognize the sensitivity of demand to price (Chapter 4).

Another alternative solution approach is the one developed by Hoganson and Rose (1984). They use the LP dual theory to develop a simulation approach that solves the large problem decomposing it into many smaller dual problems that optimize individual management unit decisions. Then, the smaller problems are tied together by the forest-wide constraints. This simulation approach and its newer transportation version, DTran, will be further explained in the following chapter because it is the solution technique used in this study.

Forest management planning models, including Dualplan/DTran, are often deterministic models. They consider all the information that takes place in the model is known. However, long-term forest planning problems are surrounded by potential uncertainties. Among all the potential uncertainties that take place in a forest management situation, climate change seems to be a critical challenge that needs to be addressed.

In a three-article format, research efforts presented throughout this dissertation are focused on addressing the potential impact of growth uncertainty surrounding climate change in forest management planning by developing a stochastic forest planning model. To
understand the effect of potential crucial parameters, several demand curves are defined for aspen timber and hardwood old forest, with and without considering that the future growth and yield is known.

Research objectives in Chapter 2 are centered on understanding the dynamic and trade-offs of integrating multiple objectives. In this paper, I study a scheduling model considering the combined production of two ecosystem services: timber and old forest production when using different demand functions, including a downward-sloping demand curve, for the production of old forest. A forest-wide application that involves several timber market outputs and multiple ownerships helps understand the impact of incorporating multiple ecosystem services into the decision-making process.

Chapter 3 focuses on the development of the multi-stage stochastic forest planning model to address the potential impact of growth uncertainty surrounding climate change. Using a deterministic forest planning model as an initial point, DTran, the main objective of this chapter is to expand upon that forest planning model to create one that explicitly accounts for uncertainty. The stochastic approach proposed decomposes problems into many stand-based subproblems that will allow us to recognize larger, more detailed, forest-wide model formulations over a relatively long planning horizon.

Lastly, Chapter 4 incorporates the main concepts reviewed in Chapters 2 and 3. A strategy to potentially deal with uncertainty in forest planning is to increase flexibility and keep the options open, to be able to adapt to several futures. Using the multi-stage stochastic forest planning model developed in Chapter 2, I compare test cases using different demand curves for aspen timber, including downward-sloping demand curves. The price-sensitive demand functions will likely provide the flexibility of adapting the harvest levels to different future scenarios, producing more resilient forest management plans by making management decisions dependent on how the future unfolds.
Chapter 2: Integrating Ecological and Economic Objectives across the Minnesota Landscape

2.1 Introduction

Forest management situations are typically complex, multi-faceted problems. Decisions often must be made incorporating broad landscape-level objectives such as wildlife population needs, forest health, and sustainable harvest; being also important to recognize stand-level details such as soil conditions, mixed tree species and/or ages, or operability (Figure 2.1). Also, long planning horizons are generally needed and many forests are mosaics of multiple ownerships. Managers want to understand the trade-offs associated with the management options available. The integration of ecological and economic objectives is considered one of the biggest hurdles for forest planning. The consequences resulting from forest management decisions made today will likely affect landscape conditions and associated ecosystem services far into the future.

The concept of ecosystem services was developed to address the linkages between ecosystems and human well-being. Ecosystem services are defined as the benefits people obtain from ecosystems (Millennium Ecosystems Assessment. Ecosystems and Human Well-being: Synthesis 2005). Due to the diversity and complexity of ecosystems and associated ecosystem services, an interdisciplinary effort is generally needed. A key to studying ecosystem services is in combining economics and ecology (Polasky and Segerson 2009). Gómez-Baggethun et al. present the history of how the economic theory has considered nature’s benefits from a Classical economics perspective up through a modern view of ecosystem services (Gómez-Baggethun et al. 2010).
Ecosystems reinforce human well-being in many ways, and this fact is acknowledged in the Millennium Ecosystem Assessment, where ecosystem services are divided into provisioning (food, freshwater, fuel, timber,…), regulating (climate regulation, erosion regulation, water quality,…), cultural (recreational, aesthetic, spiritual values,…) and supporting services (soil formation, nutrient cycling,…) (Millennium Ecosystems Assessment. Ecosystems and Human Well-being: Synthesis 2005). Both the definition and classification stated in the Millennium Ecosystem Assessment have been widely used, but other definitions and classifications of ecosystem services are highlighted in the literature (Costanza et al. 1997; Daily 1997; Costanza 2008; Fisher et al. 2009). Fisher et al., as well as Boyd and Banzhaf, argued the need to distinguish between intermediate services (considered as processes or functions in Boyd and Banzhaf) and final ecosystem services, to avoid double counting services when estimating their economic values, aggregating their values, or integrating them into a model (Boyd and Banzhaf 2007; Fisher et al. 2008). They
also discriminated between *services* and *benefits*, advocating that *services* are *benefit*-specific (Boyd and Banzhaf 2007) and that the same *service* can produce several *benefits* (Fisher et al. 2008). Boyd and Banzhaf suggested to define final ecosystem services as the components of nature or ecological characteristics that are directly used or consumed to produce human well-being, they are nature’s end-products. However, Fisher et al. promoted the idea of considering ecosystem services as the aspects of the ecosystem that are either actively or passively used to produce human well-being. Additionally, Fisher et al. also discussed using the relationships between supply and demand of the ecosystem services to evaluate and connect them to human welfare (Fisher et al. 2008).

This economic framework highlights the idea that the willingness to pay for an ecosystem service might not always be constant, depending on both the quantity and quality of the ecosystem service provided. In other words, the value of an ecosystem service is a function of marginal changes in the flow of the service produced. The marginal value could also be understood as the amount that people are willing to pay to access an extra unit of the service or the price that people would pay to avoid losing one unit. With this approach, higher marginal values will be assigned to an ecosystem service when it becomes scarce and this marginal value will decrease as the supply of the service increases. In other words, the value of additional services will depend on the level of ecosystem service already provided.

In the case of forest ecosystems, the list of services that humans can benefit from is very extensive, ranging from timber production, water regulation (quality and quantity), carbon storage, local and global climate regulation, nontimber products, or wildlife habitat. Binder et al. (Binder et al. 2017) present a detailed review of forest ecosystem services highlighting research related to ecological production functions and economic benefits functions for the different forest uses. Old forest is considered an ecological end product that could provide several benefits including wildlife habitat, recreational use, biological diversity, and/or aesthetic value. The old forest definition should not be confused with the old growth stage (or multi-aged complex (Franklin and Van Pelt 2004)) of stand development which is classified based on structure, composition, and function. The age at which a stand provides old forest services may vary by region due to differences in climate
and species. For example, in northern Minnesota, USA, many of the common species are early successional with on average life spans less than 150 years (Fire Effects Information System (FEIS) n.d.). This may be very different from other regions, for example, rotations shorter than 10 years for species of Eucalyptus (*Eucaliptus* spp.) in Brazil (Diaz-Balteiro and Rodriguez 2006) versus cutting cycles in which the maximum age of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) can be greater than 300 years in the Intermountain West in the USA (Alexander 1987). An important reason age is used to defined old forests is that it can be more easily assessed and used by forest planning models compared to structure, composition, and function.

The Multiple Use Sustained Yield Act of 1960 (P.L. 86-517) requires US national forests to be managed for outdoor recreation, range, timber, watershed, and wildlife and fish purposes. The National Forest Management Act (NFMA) of 1976 (P.L. 94-588) requires the USDA Forest Service to use a systematic and interdisciplinary approach to management planning. Forest planning models integrating multiple forest uses have been used since the 1970s. Work has ranged from developing general models that account for the production of multiple services (Bowes and Krutilla 1985) to specific models accounting for timber and wildlife production including both spatial and temporal dimensions (Arthaud and Rose. 1996; Nalle et al. 2004) or models that provide an even flow of timber production while minimizing the sediment levels settled to stream segments (Hof and Bevers 2000). Diaz-Balteiro and Romero extensively reviewed the most recent forest management problems with multiple criteria decision making (Diaz-Balteiro and Romero 2008). In addition, Filyushkina et al. compiled and analyzed the most recent studies that integrate non-market forest ecosystem services into decision making in the Nordic countries (Filyushkina et al. 2016). Borges et al. provides good detail on the role of harvest scheduling models in forest management (Borges et al. 2016). Downward-sloping demand (marginal value) curves have been explored and used in forestry, primarily for timber production (Duloy and Norton 1975; Hrubes and Navon 1976; Walker 1976, 1990). Even though studies related to ecosystem services might differ on how they define and classify the services that multi-functional ecosystems provide, there is a common
conclusion that both the economic valuation of ecosystem services and understanding benefits and costs of management options are keys to help make decisions when managing ecosystems. We also want to acknowledge that forest management is intrinsically a joint production problem. Decisions made with the interest of producing a specific ecosystem service may affect the production of other forest ecosystem services.

With the main goal of understanding better the trade-offs of integrating multiple ecosystem services, we study a harvesting schedule model considering the combined production of two ecosystem services: timber and old forest production. We use the marginal valuation approach described above to value the old forest service. Emphasis is on important details including stand-level differences in the forest cover type, stand age, ecological region, site quality, percent riparian, and distances to timber markets. We use the marginal valuation approach described above to value the services of old forest. We use an application of the model in northern Minnesota in the US to help us better understand the impact of incorporating multiple ecosystem services into the decision-making process. There is a wide range of factors that can impact the quantity and quality of old forest, such as forest cover type, the intensity of harvest levels of the main forest cover types, stand ownership, ecological region, and the successional nature of the cover type among others. With the purpose of understanding the relationship between all these factors and the production of the old forest, we analyzed (1) the production of upland hardwood old forest under different forest management options, (2) the trade-offs of using distinct marginal value functions for the production of old forest, and (3) the potential impacts of adding premium values to major forest land ownership groups to produce old forest. As is often done in forest planning, multiple model scenarios are emphasized with comparisons across scenarios adding insight on trade-offs and impacts of modeling assumptions.

2.2. Materials and Methods

We explain our approach in three steps. First, we provide an overview of and the background of the model used, Dualplan. Second, we describe the scenarios for old forest
value considered. Finally, we provide detail on our application in northern Minnesota, including an overview and description of the data, the constraints, and the scenarios.

a) Dualplan: background and overview of the model

Dualplan is a forest harvest scheduling model developed initially over thirty years ago (Hoganson and Rose 1984). Over time it has been substantially updated with diverse features and modules that give the model flexibility to describe and track important stand-level detail while addressing relatively large problems (Hoganson and Rose 1987; Hoganson and Kapple 1991; Hauer and Hoganson 1996; Hoganson and Borges 1998; Hoganson et al. 2008; Hoganson and Reese 2010). Dualplan and DTran, its multi-market, multi-ownership, transportation variant, have been successfully applied in many large studies, ranging from all-landowner-multi-market studies emphasizing timber-based economic development (Jaakko Poyry Consulting 1994; Department of Natural Resources 2006) to USDA National Forest planning emphasizing spatial arrangement of the forest for wildlife habitat (USDA Forest Service 2004a, 2004b; Hoganson et al. 2005; Wei and Hoganson 2005).

Dualplan uses a Model II linear programming formulation (Johnson and Scheurman 1977) to define the forest planning problem. It decomposes the formulation into subproblems that are each linked to the master problem via the dual variables associated with the forest-level constraints of the master problem. Forest-level constraints can range from constraints on total timber production by planning period to periodic targets for old forest characteristics. In the simplest case, each subproblem in Dualplan is an economic analysis of a specific timber stand. Analyses for each subproblem use estimated values of dual variables for the forest-wide constraints of the master problem to recognize the stand-level impacts of stand management options on the forest-wide constraints. (Hoganson and Rose 1984; Paredes and Brodie 1988, 1989). Once Dualplan develops an initial forest-wide schedule, the schedule is summarized with those results used to help re-estimate the optimal values of the dual variables for the forest-wide constraints. The subproblem solution process is
repeated iteratively, each time updating estimates of the dual variables (shadow prices) for the forest-level constraints. With its ties to duality theory, the solution process always produces optimal solutions, yet the solutions are infeasible solutions in that they typically violate at least some of the forest-wide constraints of the master problem. But the process of using the intermediate results to help-re-estimate the values of the dual variables is key to help move solutions towards feasibility. Applications have consistently found that estimates of the dual variables for the forest-wide constraints can be determined such that violations (infeasibilities) of the forest-wide constraints are acceptable in practical terms. With its ability to decompose problems into subproblems, very detailed forest-wide problems (many stands) can be addressed.

Dual variable value estimates (shadow price estimates) are central for addressing forest-level constraints in stand-level analyses. Essentially each dual variable value estimate is an added bonus or penalty to include in a stand-level analysis so that forest-level impacts of stand-level management options are addressed when they are evaluated. The level of these bonuses or penalties is often valuable information to decision-makers in selecting appropriate constraint levels (targets) for the forest-level constraints. Often a key aspect of planning is to use the analyses to help select targets or goals for the forest as more is learned about the potentials of the forest, especially in terms of realistic forest-level targets over time. Dualplan emphasizes the economic interpretation of the dual formulation of the forest-wide problem which has been emphasized as valuable information for decision-makers in planning (Paredes and Brodie 1988, 1989).

Dualplan takes advantage of the efficiencies of Model II formulations (Johnson and Scheurman 1977), where the analysis area (AA) treatment options can be defined separately for each rotation without enumeration of all possible combinations of multiple-rotation options as used in Model I formulations (Johnson and Scheurman 1977). Treatment options for existing AA conditions or for future regeneration options in Dualplan take into consideration both market type and condition type flows. Market type flows are the benefits and costs for the output product (they are assumed to occur at the midpoint of the planning period), and the condition type flows are descriptions, at the end
of the planning period, of the condition of the AA if the associated treatment option is selected. A condition type flow is a unique combination of the stand age (5-year age class), forest cover type, and site index class.

The model uses map layers of the forest and associated map colors for each layer to allow users to help define forest condition sets and market flow sets. Map layers can show stand characteristics such as ownership, ecological region, or management zone. Dualplan is extremely detailed in tracking market type flows and forest condition type flows. Condition type flows are in terms of forest area and can be aggregated into condition sets, which are groups of condition type flows defined by the user. For example, a condition set could be the total area of ‘old forest’ within a specific forest cover type and a specific ecological region. The area of the forest in every condition set is tracked by the model for each planning period. A condition type flow can belong to more than one condition set. For example, a 60-year-old stand in the aspen (Populus spp.) cover type on federal lands could be included in an “old hardwoods” condition set and in an “age 60 federal lands” condition set. Similarly, market sets are total aggregated market flows for each planning period of one or more market type flows recognized in the stand-level treatment options. Again, each market type can be part of any number of market set flows. This form of defining sets helps us define constraints applied to sets (either market or condition set) for each planning period.

Another critical facet of scheduling models is the inventory conditions at the end of the planning horizon. When the value of the ending inventory is not fully and appropriately recognized in a linear programming model results can have a tendency of liquidating or overestimating the value of ending inventory. To help overcome this inclination, Dualplan incorporates the option of projecting the dual variable estimates for periods beyond the planning horizon, thus allowing ending inventory to be valued based on modeling results. The user can decide to project the shadow price estimates of the dual variable of the last period or an average of the shadow values found for periods near the end of the planning horizon.
Because Dualplan decomposes problems into subproblems, the process fits well with computational efficiency opportunities offered by parallel processing technologies that harness multiple co-processors common today on desktop computers. Essentially, each co-processor can analyze a different set of subproblems (stands) during each iteration.

b) Old forest and its marginal value

To better understand trade-offs between the joint production of the two ecosystem services, timber and old forest, we developed a series of scenarios in which old forest is valued differently. As mentioned in the introduction the marginal approach was used to evaluate the old forest value ecosystem services and, in this section, we explain how the range of marginal value functions was chosen. We considered three types of relationship between the marginal value and old forest area: horizontal, vertical, and downward-sloping functions.

To recognize the dynamics of the model in relation to the old forest, we first considered cases in which old forest has a constant marginal value per hectare, resulting in a horizontal marginal value function. As a baseline, we assumed that environmental preferences towards old forest are absent, so that old forest is valued at $0/ha and that timber production is the sole valued service from the forest. We also considered three additional scenarios with horizontal demand curves, raising this horizontal demand curve in increments of $20/acre considering constant annual values of $49.4/ha, $98.8/ha, and $148.3/ha. These four marginal value curves essentially include the value of old forest in the objective function of the model, not forcing the production of old forest through any explicit constraints in the model.

With the intent of assessing the behavior of the model with an approach that forest planners commonly follow to sustain old forest conditions, the second set of scenarios used a fixed target amount of old forest to be achieved at the end of each planning period. These area targets imply vertical demand curves. We considered old forest targets of 0.85 million hectares, 0.93 million hectares, and 1.01 million hectares. Initially, the forest has
approximately 1.23 million hectares of old forest; in terms of financial maturity, much of the forest is over mature.

Finally, we defined and explored three additional old forest marginal value curves with a downward slope, to reflect the possibility that stakeholders place higher marginal value on scarce flows of the ecosystem service. To at least some degree, the position and shape of a marginal value function for old forest is a controversial topic, especially when little is known about the potential trade-offs of forest management. Different forest stakeholder groups have quite different values associated with old forest. For example, some in the timber industry would likely argue for keeping marginal values for old forest high for only a short range of old forest production levels and then declining rapidly with increasing quantity. By contrast, some environmental groups might suggest marginal value curves that decline slowly with increasing quantity. To incorporate both views into the study we considered two marginal value functions mimicking these preferences, as well as a third, intermediate option with a constant slope. Figure 2.2 shows these three marginal value functions; called high, medium, and low marginal value functions throughout the rest of the paper. These functions relate only to the production of old forest of upland hardwoods for our study area, which will be described in more detail in the next section.

Figure 2. 2 Downward–sloping marginal value functions used for the old forest as the ecosystem service.
All the marginal functions are assumed to be for the aggregated value of the total old forest and are assumed to be the same for each planning period. Values are in terms of forest condition at the end of each planning period and are expressed here in annual terms, representing a value that can be added (or credited) as a series of benefits over time for valuing specific stand-level management options. These marginal values vary by periods, the total area of old forest changes over time.

c) Application in northern Minnesota

The state of Minnesota is located in the north-central portion of the United States and is bordered by Canada to the north. Approximately 35% of the 22.5 million hectares of Minnesota is classified as forested (Miles et al. 2017). The forests of Minnesota are diverse and include three of Bailey’s ecosystem provinces: Prairie Parkland in the west, the Eastern Deciduous Forest through the center and southeastern section, and the Laurentian Mixed Forest in the northeast (Bailey 1983). The past glacial activity has substantially shaped topography and soil condition across the state, generating a low topographic relief landscape and a broad selection of soil conditions ranging from sandy outwash plains to rich peat bogs (Stearns 1997). The soil composition has influenced vegetation cover resulting in pine (Pinus) species commonly observed on sandier less nutrient-rich soils, hardwoods observed on nutrient-rich silt loams, and spruce (Picea), tamarack (Larix), and ash (Fraxinus) species observed in poorly drained bogs. In addition, past human actions have also had a large effect on the current forest cover in Minnesota. Agricultural conversion and intensive logging practices during the late 19th and early 20th centuries have greatly influenced current forest distribution and composition (Stearns 1997). Ownership is diverse and includes multiple forest management agencies including the USDA Forest Service, the Minnesota Department of Natural Resources (DNR), county land departments, Tribal governments, industrial private landowners, and non-industrial private landowners. Management objectives frequently vary by owner. Among public land, state and county lands are more intensely managed for timber production (Miles, Patrick
D. VanderSchaaf, Curtis L. Barnett et al. 2016). A state requirement of both state and county lands is the production of timber for revenue, some of which is used to help fund schools in the local communities. Of the federal lands, the Superior National Forest’s Boundary Water Canoe Area Wilderness (BWCAW), with an approximate extent of 400,000 hectares, is part of the National Wilderness Preservation System and it is reserved forest land and not available for timber production.

This study utilized information generated from a recent and ongoing Minnesota study (Hoganson et al. 2017). Data needs were intensive and included forest inventory data, forest inventory projections, cost estimates of silvicultural treatment options, and timber transportation cost estimates to major timber market centers in Minnesota. USDA Forest Inventory and Analysis (FIA) inventory data was used to describe and help project the forestlands in the model. The Minnesota DNR has aggregated the USDA Forest Service forest cover type classifications into eleven Minnesota forest cover types. We used that classification with a few small modifications. Aspen is the main forest cover type in Minnesota (29% of the statewide forest land), followed by black spruce (9%), oak (9%), northern hardwoods (9%), and lowlands hardwoods (9%) (Miles, Patrick D. VanderSchaaf, Curtis L. Barnett et al. 2016). The aspen forest cover type is also widely spread across the study area. It usually contains a substantial component of other species, with the mix generally containing more hardwoods in the Southwest and more conifers in the Northeast.

FIA data are collected using a nationally consistent two-phase sampling design and the program uses an annual system in which all the field plots are visited and measured once during the survey cycle. The duration of that cycle is 5 years in Minnesota, therefore one-fifth of the forestland is measured every year. The spatial sampling intensity of the FIA program in Minnesota is close to one plot per 2,428 hectares (Miles et al. 2003; O’Connell et al. 2016). Data from the FIA program are available and open to the public. The sampling design of the FIA plots allows them to be further divided into ‘conditions’, meaning that a proportion of a plot could be in a different forest condition. This could be based on differences in the forest type, ownership, forest age, or reserve status. Data for this study were collected for the 2010-2014 survey cycle. A total of 7,169 FIA plots were included,
characterizing approximately 6,046,840 hectares of forest land in Minnesota that are north of the Minneapolis-St. Paul metropolitan area, about 95% of the forest land in Minnesota. Separate AAs were used for each of all of the forest condition classes of FIA plots in the study area. Each FIA plot condition class was subdivided to reflect estimated areas in one of three riparian classes. Each FIA condition class was further subdivided into five classes to reflect timing assumptions regarding the availability of harvest. Details are described in Hoganson et al. (Hoganson et al. 2017) with availability assumptions generally varying by stand age and forest cover type.

Aspen and red pine (*Pinus resinosa* Ait.) are considered two of the most valuable tree species for the forest industry and with the highest demand in Minnesota. With the purpose of giving more realism to the model and accounting for the variability of mix species within in aspen stands, the AAs in the aspen cover type are further classified based on the ecological region with species mixes of timber yield predictions varying by ecological region (Figure 2.3), site index class and stand age. Similarly, red pine plantations are an important portion of the managed timberland in Minnesota, with a substantially higher average growth rate than other forest types. Red pine AAs were also subdivided into red pine plantations and natural stands of red pine, allowing the model to recognize higher levels of details in red pine plantations.

Figure 2. 3 Ecological regions in Minnesota. For the purpose of this study, small ecological regions were combined with a nearby section. Specifically, 212J was merged with 212K, and 251A and 251B were combined with 222M.
The model has also the ability to recognize a range of prescription options for different management systems among forest cover types. Clearcutting with residuals was considered a management option for all forest cover types. Minnesota Forest Guidelines regarding clearcutting with residuals were followed for estimating all timber yields (Minnesota Forest Resources Council. Sustaining Minnesota Forest Resources: Voluntary Site-Level Forest Management Guidelines for Landowners, Loggers and Resource Managers. 2013). Minimum and maximum rotation ages were also defined for each forest cover type and site quality class to guarantee that harvests could only happen within a reasonable age range. Detail can be found in Hoganson et al. (Hoganson et al. 2017).

In addition to clearcut options for harvest, thinning options were considered for red pine, shelterwood systems were considered for oak, and uneven-aged management options were considered for northern hardwoods. No-harvest options were considered for all AAs. Although old forest objectives are of concern for all forest cover types, this study focused on old forest production of hardwoods on uplands.

Overall, our intent is to keep the model simple enough to be useful yet realistic and aligned to the current forest situation in Minnesota. There is interest in the potential future growth of the forest industry in Minnesota and all of our scenarios considered some potential expansion of the forest industry in Minnesota. For the first 5-year planning period harvest levels were constrained to be between 13.77 and 15.22 million m$^3$. For period two and all periods beyond, statewide harvest levels were constrained to be between 14.5 and 16.31 million m$^3$. The model recognized premiums for timber by species and product class with the highest prices for red pine sawlogs. Timber prices are delivered prices to the market including harvest and transport costs.

Aspen harvest levels in Minnesota are of particular interest, because of interest for potential mill expansions and because aspen harvest levels, at least in a long-term perspective, are likely currently near their long-term sustainable level. Also, because of aspen’s general short-lived nature, much of the aspen forest cover type is of the stand age where merchantable stand volume is declining and stands in the aspen forest cover type are succeeding to other forest cover types. Aspen age-class distribution also varies
substantially by forest ownership group. The volume of aspen includes the species: trembling aspen (*Populus tremuloides* Michx.), bigtooth aspen (*Populus grandidentata* Michx.), and balsam poplar (*Populus balsamifera* L.). Recognizing the importance of aspen harvest levels, we considered three scenarios that differ in the assumed volume of aspen harvested per year, while the constraints on the statewide harvest levels are the same for these three scenarios.

The three scenarios were: (1) a first scenario that forced aspen harvest levels to be at least 5.43 million m$^3$ per year throughout the planning horizon. This is an approximate estimate of the current aspen harvest volume of recent years in Minnesota; (2) a second scenario to assess the behavior of harvest flows under a relatively small mill expansion scenario, increasing aspen harvest rates to an annual constant level of 6.16 million m$^3$ throughout the horizon planning; and (3) the last scenario where we impose an early departure of aspen volume levels at 6.16 million m$^3$ per year during the first 20 years of the planning horizon and decreasing those levels to 5.8 million m$^3$ after that, remaining at that 5.8 million m$^3$ level throughout the rest of the 100-year planning horizon.

Condition sets were defined to help track and constrain the production of old forest. The focus was on a condition set that tracked the area of old forest of upland hardwoods. The area in this condition set also included percentages of the aspen and birch (*Betula*) cover types, with percentages varying by forest cover type, stand age, and ecoregion (Table 2.2). Both aspen and birch forest cover types are generally short-lived where, if not harvested, a proportion of their area is assumed to have transitioned to a mixed hardwood condition. The transition period is a gradual time period over which the older overstory trees die and are replaced by hardwoods assumed to be in the stand. “Age” of the stand is defined in terms of the stand age at the start of the planning horizon plus time since the start of the planning horizon, with the stand forest cover type not be changed explicitly in the model. For example, the 0.3 value for the aspen forest cover type at age 100-105 in the Northeast ecoregion indicates that 30% of these aspen stands are assumed to meet old forest hardwood requirements. Generally, as reflected in Table 1, stands in the Northeast portion of the study area transition to hardwoods at a later age. We assume that a higher percentage
of the area in the aspen forest cover type produces old forest before transitioning to another forest cover type. However, as also reflected in Table 1, a lower percentage of the oldest aspen stands in the Northeast transition to old hardwoods because a substantial proportion of aspen forest cover type in this region will succeed to a mixed conifer condition. In terms of defining the area of old forest hardwoods, the birch forest cover type was not considered to produce old forest until the forest cover type changes, as birch trees are short-lived and generally do not make for good wildlife cavity trees as would aspen trees (Burns and Honkala 2008).

Table 2. 1 Percentage of the area of aspen and birch forest cover types that meet old forest requirements in each ecoregion and each stand age class.

<table>
<thead>
<tr>
<th>Forest Cover Type</th>
<th>Age class (year)</th>
<th>East (212K)</th>
<th>Northeast (212L)</th>
<th>Northcentral (212M)</th>
<th>Central (212N)</th>
<th>Southwest (222M)</th>
<th>Northwest (222N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspen</td>
<td>55-60</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Aspen</td>
<td>60-65</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Aspen</td>
<td>65-70</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td>Aspen</td>
<td>70-75</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>0.8</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Aspen</td>
<td>75-80</td>
<td>0.4</td>
<td>1</td>
<td>0.8</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Aspen</td>
<td>80-85</td>
<td>0.25</td>
<td>1</td>
<td>0.6</td>
<td>0.25</td>
<td>0.15</td>
<td>0.4</td>
</tr>
<tr>
<td>Aspen</td>
<td>85-90</td>
<td>0.15</td>
<td>0.8</td>
<td>0.3</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Aspen</td>
<td>90-95</td>
<td>0.15</td>
<td>0.6</td>
<td>0.2</td>
<td>0.15</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>Aspen</td>
<td>95-100</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>Aspen</td>
<td>100-105</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.25</td>
</tr>
<tr>
<td>Aspen</td>
<td>105-110</td>
<td>0.2</td>
<td>0.3</td>
<td>0.25</td>
<td>0.3</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Aspen</td>
<td>110-115</td>
<td>0.35</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Aspen</td>
<td>115-120</td>
<td>0.4</td>
<td>0.2</td>
<td>0.35</td>
<td>0.5</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Aspen</td>
<td>&gt; 120</td>
<td>0.5</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Birch</td>
<td>85-90</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Birch</td>
<td>90-95</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Birch</td>
<td>95-100</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Birch</td>
<td>100-105</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Birch</td>
<td>105-110</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Birch</td>
<td>110-115</td>
<td>0.25</td>
<td>0.2</td>
<td>0.25</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Birch</td>
<td>115-120</td>
<td>0.3</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Birch</td>
<td>&gt; 120</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Similar to how some timber products (like pine saw logs) have premium values, premiums for specific types of old forest conditions were also considered in some scenarios. Specifically, in addition to the aforementioned scenarios, we also conducted a sensitivity analysis to understand the potential relationship between old forest and stand ownership, using premiums based on stand ownership and on stand age within each forest cover type. These premiums are summarized in Table 2. Generally, in terms of ecosystem services, it may be more desirable to have the older hardwood conditions emphasized more on lands open to the public, and potentially more aggregated on the landscape through specific areas like on National Forest system in Minnesota.

Table 2. Premiums considered for old forest for the low and high marginal value function scenarios for old forest of upland hardwoods based on forest cover type and stand age class ($/ha/year).

<table>
<thead>
<tr>
<th>Premium Level</th>
<th>Forest Cover Type</th>
<th>Age (Year)</th>
<th>Federal</th>
<th>State</th>
<th>County</th>
<th>Private</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Oak &amp; N. Hardwood</td>
<td>60-79</td>
<td>9.88</td>
<td>7.41</td>
<td>4.94</td>
<td>0.00</td>
</tr>
<tr>
<td>Low</td>
<td>Oak &amp; N. Hardwood</td>
<td>80 and older</td>
<td>11.86</td>
<td>9.39</td>
<td>6.92</td>
<td>1.98</td>
</tr>
<tr>
<td>Low</td>
<td>Aspen</td>
<td>60-74</td>
<td>1.98</td>
<td>1.48</td>
<td>0.99</td>
<td>0.00</td>
</tr>
<tr>
<td>Low</td>
<td>Aspen</td>
<td>75-90</td>
<td>3.95</td>
<td>3.46</td>
<td>2.97</td>
<td>1.98</td>
</tr>
<tr>
<td>High</td>
<td>Oak &amp; N. Hardwood</td>
<td>60-79</td>
<td>19.77</td>
<td>14.83</td>
<td>9.88</td>
<td>0.00</td>
</tr>
<tr>
<td>High</td>
<td>Oak &amp; N. Hardwood</td>
<td>80 and older</td>
<td>23.72</td>
<td>18.78</td>
<td>13.84</td>
<td>3.95</td>
</tr>
<tr>
<td>High</td>
<td>Aspen</td>
<td>60-74</td>
<td>3.95</td>
<td>2.97</td>
<td>1.98</td>
<td>0.00</td>
</tr>
<tr>
<td>High</td>
<td>Aspen</td>
<td>75-90</td>
<td>7.91</td>
<td>6.92</td>
<td>5.93</td>
<td>3.95</td>
</tr>
</tbody>
</table>

For all the scenarios modeled, we used a 100-year horizon planning divided into twenty 5-year periods. To calculate the net present value of all stand-level management options a 4% annual discount rate was used for all scenarios. To help the reader understand better the current situation for the study area, Figure 2.4 shows, by forest ownership, the age class distributions for the main cover types at the start planning horizon. In Minnesota, the rotation age for aspen cover type is usually 40 - 45 years, 80 - 90 years for oak and northern hardwood cover types depending on the site quality, and 50 years for the birch cover type.
Figure 2.4 shows the current relative abundance of financially over mature imbalance for both aspen and birch cover types for timber production, as well as the fact that the majority of the oak and northern hardwoods timberland are on private lands. The graphs also use the same scale, helping illustrate the current balance of these four forest cover types central to this study.

![Figure 2.4 Current age-class distribution of aspen (a), oak (b), northern hardwoods (c), and paper birch (d) cover types at the beginning of the planning horizon (period 0) in the study area](image)

2.3. Results

Results are presented in five subsections (1) Old forest and timber production across different aspen harvest levels; (2) results related to the behavior of the different horizontal marginal functions for old forest for the middle aspen harvest level; (3) results showing the
impact of targeting a fixed quantity of old forest; (4) Downward-sloping marginal functions use for old forest evaluation; and (5) sensitivity analysis of premium levels across forest ownership.

a) The joint production of old forest and timber across different aspen harvest levels

One of the goals of this study is to assess the joint production of old forest with several alternative aspen harvest levels. As mentioned earlier, aspen is one of the main forest cover types in Minnesota, both in area and in harvest levels. With a high old forest marginal value function, the amount of old forest produced under the three aspen harvest levels is similar among scenarios and follows the same pattern (Figure 2.5a). It peaks during the first period under all three scenarios and it gradually decreases until period nine. This fact is again correlated with the current forest condition for the forest cover types considered producing old forest. In period ten, when the aspen stands harvested in periods one and two are available to harvest again, the marginal value for old forest slightly increases, favoring holding the stands to create old forest. Differences among scenarios are greater in the shadow values associated with the aspen constraints. For the low aspen harvest level scenario (5.44 million m$^3$ annually) shadow values remained zero (or very close to zero) during the first four periods and during the last ten periods (Figure 2.5b) and shadow prices were always under $5.2/m^3$ during the rest of the periods. However, these values substantially increased under the high aspen harvest level scenario (6.16 million m$^3$ annually), implying that achieving the highest harvest level for aspen may be difficult to sustain throughout the planning horizon. Aspen shadow prices for the medium aspen harvest level followed a regular pattern (Figure 2.5b). They gradually increase in value until they reach the maximum value in period eight, and they slightly decrease afterward when the aspen area harvested in period one is again available to harvest.
The shadow price estimates for the volume constraints applied to all the species follow the same pattern across aspen harvest levels (Figure 2.6). For earlier periods, these shadow prices are negative, acting as penalties that maintain lower timber flows. These values increase over time, eventually becoming positive subsidies encouraging harvest in later periods. Essentially, these shadow prices reflect the initial overmaturity of the forest (financially), with a fairly steady increase in returns for delaying harvests until later periods to offset stand-level volume growth rates that are below the interest rate for a large percentage of the forest in most cover types.

Figure 2.5 Amount of old forest produced under three aspen harvest levels and the high marginal value function for old forest (a) and aspen shadow prices for the three aspen harvest levels and the high marginal value function for old forest (b).
Results from the models using the different aspen harvest levels suggest the medium aspen harvest scenario is most plausible, so we use that scenario for the rest of the paper. The lowest aspen harvest level yields zero shadow value during several periods, suggesting that aspen harvest levels could be increased. In contrast, the high aspen harvest level scenario may not be sustainable in the long term. The medium aspen harvest scenario entails an early departure of an annual level of $6.16 \times 10^6$ m$^3$ of aspen during the first 20 years, decreasing to 5.8 million m$^3$ in period six and remaining constant throughout the rest of the planning horizon.

b) Horizontal marginal functions for old forest (fixed and constant price)

One of the easiest ways to promote a non-common use of forests is by giving a reward for that use. For old forest, the area of forest that is producing old forest is not harvested. This
section assesses the potential impact of a fixed price incentive for old forest, a common implementation practice. With this approach, each stand-level treatment option is rewarded a price in each planning period it produces old forest. Under this set of scenarios, this per-unit price is fixed regardless of the amount of old forest produced forest-wide. In other words, the marginal value function is a horizontal function with respect to the forest-level quantity of old forests. As mentioned earlier, we considered four horizontal marginal value functions, with a constant annual price of $0, $49.4, $98.9, and $148.3 per hectare of forest retained to produce old forest.

As expected, a higher value assigned to old forest generally led to a larger area of old forest produced across the planning horizon. The difference between the amounts of old forest produced by marginal functions becomes larger during the middle periods and decreases considerably at the beginning and the end of the horizon planning (Figure 2.7a). For example, the ratio of the two extreme marginal functions - no value and the $148.3/ha scenarios- is more than two during periods 8 to 13, but there is little difference between the two extreme scenarios at both the beginning and the end of the planning horizon.

![Figure 2. 7 Amount of old forest produced under the horizontal marginal functions (a) and marginal values associated with the aspen volume constraints (b).](image)

A horizontal marginal function that assigns a constant value to the old forest service generally produces an irregular flow of old forest through the planning horizon (Figure 2.6a). The largest difference is found for the no-old-forest-value scenario. For that scenario,
the maximum area of old forest is produced during the first period. That result reflects the current state of the forest in Minnesota, where a large proportion of the forests is financially over mature. When no value of old forest is considered, timber production is the only ecosystem service driving the harvesting schedule, resulting in a substantial decline in old forest, dropping from 1.23 million hectares in period one to 653,169 hectares in period six. The range of old forest produced in each scenario becomes smaller as the value for old forest increases. For the case of the highest value, the differences among periods are smaller, finding the smallest quantities of old forest towards the end of the planning horizon (periods 17 to 20).

The financially mature situation of aspen forests in Minnesota is also reflected in the marginal values associated with aspen volume constraints (Figure 2.7b). The general trend for the different marginal functions is an increase in shadow price overtime over the first eight periods. The explanation for that behavior is the forest is over-rotation age in period one. If the model did not have the aspen volume constraints built into it, more aspen would be harvested in period one. Including these constraints, the model needs to hold more area to be harvested in the following periods and the only manner to encourage harvesting later is to increase prices for later periods. Shadow prices for period nine generally decrease because the area of aspen regenerated in period one is available to be harvested again in period nine. This pattern is found in the four scenarios considered in this subsection, but the values of the shadow prices associated with the different scenarios completely depend on the marginal function applied. Shadow prices for the $148.3/ha scenario are especially high in the middle periods, being more than 11 times higher than the shadow values for the non-value scenario in period eight (Figure 2.7b).

The shadow prices for the four scenarios used to compare different vertical marginal revenue curves for old forest had shadow prices for the all-species total harvest volume constraints that similar patterns and levels to those shown in Figure 2.6 (Figure 2.8).
Figure 2. 8 Shadow prices estimates for the all-species volume constraints across all the four fixed marginal value scenarios.

A horizontal marginal function for the old forest produces a very imbalanced old forest flow across periods and relatively large and substantially higher shadow prices for the aspen harvest level constraints for some periods for the two scenarios with the highest shadow prices for old forest.

c) Vertical marginal functions for old forest (fixed and constant quantity of old forest)

Another common strategy in forest planning for addressing old forest is to fix a constant target level or goal of old forest flow throughout the planning horizon. Public agencies generally use these forest policies (i.e.: retain 10 or 15% of the forest to produce old forest). Of interest is the implied marginal values (or costs) of these constraints, both in terms of general level and fluctuations over time. For the scenarios of this subsection, we constrained the model to always obtain the same quantity of old forest each period regardless of how expensive it is. This commonly applied policy resulted in shadow price
estimates that varied greatly over time for both old forest targets and aspen volume targets (Figure 2.9).

Marginal values for old forest when applying a fixed target vary from an annual value of $0 to $341 per hectare of old forest, for the higher scenario of 1.01 million hectares of old forest. For the three scenarios applied in this section, the marginal value of old forest is zero (or close to zero) for the first 5 periods implying again that there will not be any extra cost of holding more old forest because the fixed target of old forest has already been met. The pattern of the marginal values is the same for the three targets considered, but higher targets of old forest required higher marginal values in later periods. Specifically, values for the highest scenario (1.01 million ha) increase substantially at the end of the planning horizon, being greater than $200/ha/year for the last three periods and reaching an annual $342/ha during the last period. Figure 2.9a presents the precise description of the interest in using a downward-sloping marginal function to valuate old forest. Marginal values for old forest are zero across old forest targets during the first four periods. That implies that the three targets are reached on those periods and an extra hectare of old forest would not add any value once the constraint has been met. Similarly, the large marginal values for old forest at the end of the planning horizon suggest that the targets are very expensive to achieve and very large subsidies must be offered to encourage to hold a hectare to produce old forest.

Figure 2.9 Marginal value estimates for old forest under three fixed old forest target levels (a) and marginal values associated with the aspen species volume constraints with these old forest target levels (b).
Shadow prices for the aspen harvest constraints follow the same pattern across all the scenarios considered in this subsection. Values increase from zero or close to zero in periods one and two to peak in period eight. Values in this period vary across target levels, reaching almost double for the 1.01-million-hectare scenario than for the 0.85 million hectare scenario (Figure 2.9b). For these scenarios we also can see how the aspen shadow prices slightly increase at the end of the planning horizon, encouraging aspen harvest to be postponed for later periods.

Results from this and the former subsection suggested the idea of using a declining marginal value function as the method for evaluating old forest. The next subsection discusses the results found on the application of the three downward-sloping marginal value functions on the medium aspen volume scenario.

d) Downward-sloping marginal functions

The purpose of this subsection is to show some of the options that a forest planner would encounter when working with different stakeholders or landowners that differ on the ‘value’ assigned towards one of the ecosystem services. It is important to know the interactions and possible trade-offs between ecosystem services before deciding to apply a specific policy for forest planning. For the medium aspen harvest level assumption described earlier, we developed three scenarios using the low, medium, and high marginal value functions explained in subsection 2.2.

Old forest flows and their marginal values follow a different trend across scenarios (Figure 2.10). For the low marginal function scenario, old forest area starts in period one with its maximum value, 1.18 million hectares, and with a very low marginal value associated with it, close to zero. The area of old forest in that scenario decreases over time until period nine. When the old forest area is slightly decreasing the associated marginal values must increase, due to the definition of the downward-sloping function used to value old forest: the scarcer the service is, the higher the marginal value given to the service. This is also
aligned with what we see in Figure 2.10b between periods one and nine. From period nine to the end of the planning horizon both, the area of old forest and its marginal value, remain approximately constant over time.

These trends are different for the medium and high marginal value function scenarios. As it is expected, values of the amount of old forest and the marginal values for the high marginal value scenario are always higher than the ones for the medium scenario. The area of old forest produced in both scenarios decreases from the maximum amount of old forest reached in period one, to period nine. However, in these two scenarios, the amount of old forest produced grows again until period 12, and after that, it gradually drops until it reaches the minimum amount of old forest in period 20 (Figure 2.10a).

For these two scenarios, marginal values associated with old forest are substantially higher than the values for the low scenario. That difference is largest at the end of the planning horizon where the marginal value for the highest scenario reaches $180/ha/year, more than 4 times bigger than the value in period 20 for the low marginal value function scenario, $83.6/ha/year (Figure 2.10b).

Differences in value were also found in the shadow prices for aspen harvest levels, but the pattern followed by the three scenarios is similar: an increase in shadow prices until period 8 and a gradual drop in values for the next three periods. In period 12, higher subsidies are
offered to promote holding aspen harvest level and be able to meet the aspen level constraints in later periods (Figure 2.11).

![Graph showing marginal value estimates for old forest under three marginal value functions (a) and marginal values for the aspen species volume constraints across marginal value functions (b).](image)

Figure 2.11 Marginal value estimates for old forest under the three marginal value functions (a) and marginal values for the aspen species volume constraints across marginal value functions (b).

A key aspect of any forest policy is also how it impacts the other conditions or characteristics of the forest not directly related to the policy. One of the potential concerns of an old forest policy could be how it interacts with younger age classes during and at the end of the planning horizon. The impact of the two extreme marginal value functions on the age-class distribution of the forest cover type that contribute to the production old forest was the same by forest cover type, with the difference that the high marginal value produced a larger amount of old forest than the low marginal function scenario. The age-class distribution for northern hardwoods under a low old forest marginal value function is presented in Figure 2.12. Figure 2.13 shows the age-class distribution for the same forest cover type under a high old forest marginal value function.
Figure 2. 12 Northern hardwoods age-class distribution under the lowest old forest marginal value function at year 40 (a), 60 (b), 80 (c), and 100 (d) of the 100-year planning horizon.

The impact of the high old forest marginal value scenario (Figure 2.13) on the northern hardwood age-class distribution over time clearly differs from the impact observed under the low marginal value scenario (Figure 2.12). Results show an increase in the area assigned to the oldest class (> 140 years), and that difference is already patent at year 40 (Figure 2.12a and Figure 2.12b). The difference in the amount old forest area produced by different scenarios in this forest cover type is more abrupt at the end of the planning horizon, being around 200,000 hectares for the low marginal value function to more than 400,000 hectares in the high marginal value function (Figure 2.12d and Figure 2.13d).
e) Premiums levels for old forest by ownerships and age

Values of ecosystem services almost certainly vary by ownership and age class. Here, we compare the results of nine scenarios, with scenarios varying combinations of the three downward-sloping marginal revenue curves for old forest of upland hardwoods (Figure 2.2) and the premium level assumed for types of old forest (Table 2.2). Generally, public land management agencies question to what extent the public should rely on private landowners producing old forest. At the start of the planning horizon, there are an estimated 1.23 million hectares in the oak and northern hardwoods cover types in our study area and nearly 723,000 hectares are on private lands. Table 2.3 shows the amount of these two cover types that are over 80 years old at three points in time: the start of the planning horizon, the end of the planning horizon, and the midpoint of the planning horizon (period ten). Table 2.3 shows some clear trends. First, under all nine scenarios, private lands have
well over half of the old forest area regardless of the premium assumed. Second, there are some relatively distinct trends in old forest levels by ownership. Note the values in Table 3 on Federal lands double over the planning horizon under all scenarios. This is not surprising, as noted earlier, the BWCAW lands cannot be harvested and most of BWCAW is federal land. Yet the older forest totals for federal lands are not large compared to other ownerships because much of the oak and northern forest types in Minnesota are not in the BWCAW.

As one would expect the premiums assumed for old hardwoods are causing some shifts in the ownership where old hardwood conditions are scheduled, but the impact of the marginal value function for old forest has a much larger impact than the premium levels we assumed. For the high premium scenario, we assumed a premium as high as $23.72/ha/year which would translate to a $593/ha net present value for a stand in the initial inventory that can provide old forest conditions indefinitely. However, the premiums do not result in much of an increase in old forest. As shown in Table 2.3, the net increase in old forest in the northern hardwoods and oak forest cover types never exceeds 29,000 ha. In contrast, the totals shown in Table 2.2 vary by about 250,000 ha in both periods 10 and period 20 between the low and high demand scenarios (Table 2.3).
Table 2. Comparison of model results for nine scenarios in terms of the impact of premiums used for old forest based on ownership, forest cover type and stand age.

<table>
<thead>
<tr>
<th>Landowner Group</th>
<th>Period</th>
<th>High Old Forest Demand</th>
<th>Medium Old Forest Demand</th>
<th>Low Old Forest Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Increase in Old Forest (ha)</td>
<td>Increase in Old Forest (ha)</td>
<td>Increase in Old Forest (ha)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No Premium</td>
<td>Low Premium</td>
<td>High Premium</td>
</tr>
<tr>
<td>Federal</td>
<td>0</td>
<td>37,484</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Federal</td>
<td>10</td>
<td>82,888</td>
<td>11,584</td>
<td>20,690</td>
</tr>
<tr>
<td>Federal</td>
<td>20</td>
<td>100,486</td>
<td>9,243</td>
<td>16,544</td>
</tr>
<tr>
<td>State</td>
<td>0</td>
<td>53,118</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>State</td>
<td>10</td>
<td>91,234</td>
<td>4,095</td>
<td>14,383</td>
</tr>
<tr>
<td>State</td>
<td>20</td>
<td>83,456</td>
<td>2,837</td>
<td>10,148</td>
</tr>
<tr>
<td>County</td>
<td>0</td>
<td>41,206</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>County</td>
<td>10</td>
<td>72,241</td>
<td>7,325</td>
<td>12,596</td>
</tr>
<tr>
<td>County</td>
<td>20</td>
<td>64,825</td>
<td>4,842</td>
<td>9,020</td>
</tr>
<tr>
<td>Private</td>
<td>0</td>
<td>218,132</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Private</td>
<td>10</td>
<td>372,616</td>
<td>-11,262</td>
<td>-22,128</td>
</tr>
<tr>
<td>Private</td>
<td>20</td>
<td>345,254</td>
<td>-9,046</td>
<td>-15,492</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>349,941</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>10</td>
<td>618,979</td>
<td>11,742</td>
<td>25,541</td>
</tr>
<tr>
<td>Total</td>
<td>20</td>
<td>594,021</td>
<td>7,877</td>
<td>20,219</td>
</tr>
</tbody>
</table>
2.4. Discussion

Like the information summarized in Figure 2.1, the forest management situation in Minnesota is complex. Management choices are clearly impacting the ecosystem services provided. Structuring a model to address such complexities is clearly a challenge. Here, we discuss briefly a few insights from our experiential learning associated with this study that may be helpful for studies elsewhere.

a) Benefits of using downward-sloping marginal value curves

Modeling results for our scenarios suggested limitations of using constant prices or constant targets for ecosystem services. Initial age-class distributions for the forest are imbalanced, extremely so for some forest cover types. Our results showed that with constant marginal values assumed for old forest, substantial fluctuations occur in the old forest output levels over time, with levels declining more in later periods for the values we considered. In contrast, when setting old forest targets constant over time, targets were achieved at low-cost short term with substantially higher marginal costs in later periods. Downward-sloping marginal revenue curves fit well with basic concepts of scarcity, reflecting higher marginal values when resources are scarcer. Such an approach also helped overcome problems with setting infeasible or unrealistic old forest targets. With these downward-sloping target levels, targets can vary based periodically, on their associated marginal cost. In simple terms, users have the opportunity to define targets based on associated costs at the margin. Often in forest planning, it is important to consider targets for management, yet such targets are difficult to set until more is learned through analysis about production possibilities. And in forestry, these possibilities potentially changing substantially over time as forest conditions change. Also, the temporal scale is important, as old-forest values are typically time series of benefits at the stand level, with it generally important to plan ahead.
b) Importance of forest-level analysis across forest cover types

Our applications also demonstrate some of the difficulties and over-simplifications of addressing forest cover types separately. The composition of individual stands changes with succession, resulting in a shift or change in the forest cover type. This is especially true for short-lived species like aspen. Stands change forest cover type over time, especially when short-lived trees are involved. Unless natural disturbance rates are high, relatively new forest reserve areas will take time to develop into a more steady-state old forest condition, and even then, forest-level conditions will vary substantially over time unless we are dealing with very large landscapes. Some forest cover types, like aspen in Minnesota, are critical for sustaining local timber economies. Other forest types, like northern hardwood, are more complex in ecological structure and may be better suited for producing a mix of economic and ecological benefits, especially if uneven-aged management can be financially viable. Our results also demonstrate that the general wood supply situation in Minnesota, in terms of its ability to support additional economic development, is especially sensitive to specific tree species needed for development opportunities in question. Although aspen is of major value to the existing forest industry in Minnesota, opportunities for additional expansions based primarily on aspen would likely cause substantial timber supply challenges to the existing forest industry. The situation is quite different for other species and forest cover types. Generally, most of Minnesota’s forest cover types are currently financially over mature, as is consistently shown in all our scenarios with the forest-level “even flow” harvest volume constraints at their upper bounds in early periods and at lower bounds in later periods. And even without considering climate change impacts, with Minnesota currently having a preponderance of older stands that are currently growing slowly, it does not seem all that surprising that forest insect and disease outbreaks are increasing and could be quite devastating, especially for some forest cover types.

c) Benefits of Analysis Across Ownerships
With Minnesota having a mosaic of ownerships, there is clear value for large ownerships to better understand their management situation in a forest-wide landscape context. This was one clear need identified by a major recent analysis of Minnesota DNR timber harvest levels (Minnesota Department of Natural Resources. DNR sustainable timber harvest analysis. 2018). Additionally, for economic development opportunities, one cannot fully understand the supply situation if it is not analyzed over a broad landscape recognizing the details of market demands. Another consideration is the production of fewer timber products, but timber products more valuable. Emphasizing more the value than the quantity of timber produced, will almost certainly integrate better with additional objectives associated with ecological services.

It is also important to recognize that our analyses have used optimization modeling, including nonmarket objectives. Our intent is not to show predictive results but to help identify needs and understand trade-offs. Certainly, one cannot control private landowner behavior directly through broad landscape-level harvest scheduling. For example, our results certainly suggest harvesting more of the older aspen on private lands in the short-term, as otherwise substantial volumes will be lost from the market for what appears a relatively tight timber supply situation for aspen that may continue for forty years or more.

d) Additional details, data needs, and further analysis

Results are certainly sensitive to assumptions about private landowners. Detailed data on the behavior of private landowners in Minnesota and elsewhere is limited at best. However, the fact that a financially over-mature aspen stand is even present on the landscape suggests that this landowner is unlikely to harvest this stand in the near future – many of these landowners have been approached by wood procurement foresters in the recent past and declined harvest offers. Modeling results are also certainly sensitive to basic data involving growth and yield data, especially for the aspen for cover type. The recent statewide Minnesota DNR study highlights this need (Minnesota Department of Natural Resources. DNR sustainable timber harvest analysis. 2018). Specifically, this study points out the
sensitivity of their results to the aspen growth and yield data used. Aspen timber prices are also very sensitive to seasonal limitations on harvests which we did not address in our scenarios. Limited information is also currently available on harvest costs. And although FIA inventory data is relatively current, future work might look at the potentials of integrating inventories from major landowners into a landscape analysis. This would help allow for more site-specific and spatial detail which are important for ecosystem services. And how short-lived cover types will change forest cover types over time is certainly not clear. In Minnesota and elsewhere, detailed analyses for forest planning help identify important information needs for forest management.

2.5. Conclusions

Numerous facets of a forest management situation may impact forest management decisions, especially when management involves multiple objectives. This study examined the integration of timber production with the production of old forest of upland hardwoods across all forest ownerships in northern Minnesota. Results from a harvest scheduling model were compared for nineteen scenarios. Comparisons provided specific insight on the Minnesota situation related to ecosystem services. Broader insights for future efforts for other regions include:

- A marginal value approach utilizing downward-sloping marginal value functions was useful for integrating objectives. It recognizes that marginal value depends on relative scarcity. With this approach, management targets are cost sensitive, helping overcome problems related to setting ecosystem production targets or values for each planning period prior to analysis. It is a comprise approach, marginal values for ecosystem services can vary between planning periods as their associated production level fluctuates. This tends to help dampen large periodic shifts in marginal costs or production levels.
• The decomposition approach for harvest scheduling that was used in this study proved valuable, allowing recognition of substantial detail in stand-level analyses, including explicit ties to forest-level constraints. The study utilized parallel processing with total computation time not being a factor. With the model, multiple map layers portraying forest condition measures can be tracked, valued, and constrained by each planning period relatively easily.

• Coordination of management across forest cover types is important, especially when early successional forest cover types are involved and initial age classes are imbalanced. Inefficiencies in timber production associated with high timber mortality can add additional pressures for harvesting more of the forest to meet timber needs. More effectively managing some stands for timber production can help provide opportunities for emphasizing other ecosystem services in other areas of the forest.

• Collaboration across ownerships is potentially important for more effective forest management. Ownerships likely have different mixes of forest cover types, with differing age class imbalances. Forest management opportunities and needs for specific ownership groups can be better understood when considered from a multi-owner landscape perspective.
Chapter 3: Recognizing Uncertainty in Forest Planning: Addressing Growth Uncertainty Surrounding Climate Change Using a Decomposition Model for Large Landscapes

3.1. Introduction

Forest ecosystems are complex; multiple ecological, economic, and political aspects influence forest-planning decisions. Decision models have been widely used in forest management planning, but most are deterministic models, where all model parameters are assumed to be known. However, forest planning decisions predominantly concern large areas, long planning horizons, multiple outputs, numerous markets, and several stakeholders, which tend to increase the sources of uncertainty (Kangas and Kangas 2004; Yousefpour et al. 2012; Pasalodos-Tato et al. 2013). Generally, uncertainty could be defined as a lack of information, that may or may not be obtainable (Kangas and Kangas 2004). Uncertainty can result from the presence of measurement imprecisions or the absence of reliable data, it might be defined by a set of parameters representing information about the future state of nature, or it might be associated with the preferences of the decision-maker.

In forest planning, uncertainty can be related to either the stand-level or forest-wide information (Hoganson and Rose 1987). Uncertainty concerning forest-wide data, such as timber prices or climate change, has an impact on most of the forest. On the other hand, uncertainty regarding stand-level data would likely tend to “average out” over a forest.

Stochastic programming explicitly includes uncertainty in the model (Birge and Louveaux 2011). In 1955, Dantzig recognized the importance of the timing of decisions relative to the resolution of the uncertainty (Dantzig 1955). Some decisions must be made in the short run before any additional information becomes available (first-stage decision variables). Some decisions can be delayed until the second stage after new uncertainty outcome information is available. When the uncertainty is revealed, a recourse action is taken that depends on both the first-stage decision and the revealed uncertainty outcome. A stochastic model that recognizes this aspect of uncertainty is commonly known as a recourse model,
programming with recourse, or a multi-stage stochastic model. It can involve potentially many stages with each stage adding more information about the uncertain future. Some of the forestry applications of the recourse model have considered the uncertainty on timber prices (Hoganson and Rose 1987), the timber supply under risk of fire (Boychuk and Martell 1996a), or the impact of climate change (Garcia-Gonzalo et al. 2014).

A stochastic programming model can be viewed as a mathematical programming model with uncertainty about the values of some of the parameters. Instead of single and defined values, these parameters are then described by distributions or by stochastic processes (Kaut and Wallace 2007). Simplifications are often needed with these models as the models grow exponentially with the number of stages and the number of uncertain (chance) outcomes recognized for each stage. Except for some trivial cases, these problems cannot be solved with continuous distributions or with discrete distributions with too many outcomes, due to the complexity of the decision model together with the limitation of computing power. Therefore, in most practical applications, the distributions of the stochastic parameters need to be approximated by discrete distributions with a finite and limited number of outcomes. The discretization is usually called a scenario tree or an outcome tree (Figure 3.1). Then, by assigning probabilities to the possible scenarios, expected values could be used in the objective function.

An important requirement in a multi-stage stochastic programming problem is the non-anticipativity principle. This condition ensures that the decisions made at a specific period t are the same in all the scenarios that share that node (Wets 1975). In other words, given two scenarios, if the discrete representation of the two scenarios shares the same path until period t, all the decision variable values for each scenario for this path must be equal up to period t. This requirement can be expressed by explicitly defining a set of constraints on each time period that forces the equality of the decision variables of each scenario. On the other hand, an implicit formulation can use shared variables at each node in the scenario tree. With an implicit formulation, the non-anticipativity constraints are automatically satisfied.
The idea of using decomposition techniques to solve stochastic programming models will help to tackle bigger problems. One decomposition approach used on the most recent forestry applications of stochastic recourse models (Veliz et al. 2015; Bagaram et al. 2019; Garcia-Gonzalo et al. 2020) is the Progressive Hedging (PH) algorithm (Rockafellar and Wets 1991), a scenario-based decomposition technique. Each scenario is first solved as an independent problem. The initial solutions of each scenario unlikely satisfy the non-anticipativity principle. To satisfy it, the PH algorithm penalizes the deviation from the average value in all scenarios. This process is repeated iteratively until convergence.

Even though some of these forestry studies explicitly integrate uncertainty into the problem, test cases use either a short planning horizon or a relatively small forest size. The fundamental goal of this paper is to develop a multi-stage stochastic model that helps us explore how the uncertainty surrounding growth and yield of the main forest cover types can be recognized in developing a forest management plan for large areas over a relatively long planning horizon. Because our proposed stochastic approach will decompose problems into many stand-based subproblems rather than scenario-based forest-wide subproblems; larger, more detailed, forest-wide model formulations can likely be recognized. Furthermore, the process likely fits well with computational efficiency opportunities offered by parallel processing technologies on desktop computers. Essentially, each co-processor can analyze a different set of subproblems (stands) during each iteration of the solution process.

As mentioned earlier, the nature of forest planning problems encompasses several sources of uncertainty. Addressing the impact of climate change on forests is often considered a major challenge and therefore a priority. There is a lack of understanding about how the changing climate will likely affect forest ecosystems and how soon such changes could occur. In this chapter, I focus on a forest planning model that explicitly recognizes uncertainty surrounding changes in growth and yield of tree species over time.

The stochastic forest planning framework presented in this chapter has been successfully tested using a large and detailed application. Test cases include approximately 100,000
analysis areas, 20 five-year planning periods, seven major timber market centers, and eight to 16 climate change scenarios (futures). Besides this emphasis on stand-level detail, the focus is on understanding how forest management decisions would vary depending on specific assumptions describing forest-wide growth and yield uncertainty unfolding over time (i.e. the tree scenarios used to represent uncertainty). The intention is to compare several tree scenarios to understand the implications on the forest management plan. A primary objective of the model is to help identify management actions (decisions) for the short-term that will perform relatively well regardless of how uncertainty unfolds. Results can thus help forest managers by identifying strategies that adapt and respond well to climate change challenges as the uncertain future gradually unfolds.

3.2. Methods

a) Forest-Wide Uncertainty

Forest-wide uncertainty is represented using a scenario or outcome tree, where each branch in the tree represents a different plausible outcome about the uncertain future. The uncertainty tree is defined by stages and states. Each stage represents a time period or set of time periods where uncertain information about the future remains unchanged. At the end of each stage, more information about the future is learned and branches (arcs) transition each stage to a state at the start of the next stage. In this sense, learning can be interpreted as some resolution about uncertainty. Each possible path through the uncertainty tree represents a different possible forest-wide future (scenario), with each scenario typically sharing some branches with other scenarios.

Figure 3.1 shows an example of a forest-wide uncertainty tree that is defined by four stages. In this example, every time there is new learning about the future there are only two possible branches (outcomes). At the end of the planning horizon, there are eight possible scenarios or futures, each involving a unique path through the uncertainty tree network.
b) Uncertainty in Stand-level Decision Trees

This forest-level stochastic description of uncertainty is then integrated into stand-level decision trees, helping find the stand management decisions that will perform best over an uncertain future. Figure 3.2 illustrates the stand-level management decision tree and the impact of the forest-wide uncertainty for early periods in the decision tree. When solving for a specific stand, a stand-level management decision needs to be made on each decision node, i.e. each box in the network in Figure 3.2. The management decision is defined as whether it is optimal to harvest the stand at that point in time or let it grow and postpone its harvest to a later period. Harvesting is assumed to happen at the midpoint of planning periods. Decision nodes in Figure 3.2 potentially have a path that leads to a bare-land node, box number 0 in Figure 3.2, which represents the option of harvesting the stand at that planning period. Harvesting the stand in a specific planning period is linked to the bare-land node to find the optimal forest management decisions for future rotation. Letting the stand grow (top arc from box number 1 for period t+1 in Figure 3.2) the forest-level uncertainty (black circle) influences the stand, having two possible branches: forest-wide growth condition 1 and forest-wide condition 2, being those conditions more or less
favorable for the growth of each stand type. For each of these forest-level outcomes, there is a set of probabilities defined, with the optimal solution finding the expected value of the one node at the start of time $t$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{decision_tree.png}
\caption{A portion of a stand-level decision tree with forest-level uncertainty (chance nodes) included. The numbers in each square node represent the corresponding state within the stage. The shaded nodes represent the bare land condition that follows immediately after harvest.}
\end{figure}

The problem at the stand-level is solved using a backward recursive approach through time, as in evaluating harvest options it is important to link that evaluation with the value of future rotations. This solution approach provides useful information for adaptive forest management, as it gives us an insight into which path to follow throughout the planning horizon for each forest-wide future. To start the backward solution approach, an estimate of the bare land value at the end of the planning horizon is used to value network paths associated with each of the possible stand ages at the end of the planning horizon.
c) The Forest-Level Deterministic Model: DTran

The main objective of a forest-level problem, in contrast to a stand-level management problem, is to obtain the best combination of stand treatment schedules to maximize the forest-wide objective function while satisfying the constraints for the whole forest. Forest-wide constraints can be of many types, including timber targets, even-flow constraints, old forest targets, budget limitations, carbon sequestration, or biodiversity goals.

The forest-level scheduling model used as a starting point for developing a recourse model for this study is DTran, an enhanced variant of Dualplan, that was initially developed over 30 years ago (Hoganson and Rose 1984). Dualplan has been successfully used in many large-area applications (USDA Forest Service 2004b, 2004a; Hoganson et al. 2005; De Pellegrin Llorente et al. 2018). DTran extends Dualplan to incorporate multiple timber market options while eliminating the need to enumerate all market shipment options a priori as is typically done in multiple-market linear programming formulations. DTran was used for a widely recognized statewide generic environmental impact statement in Minnesota to explore timber-based economic development opportunities (Jaakko Poyry Consulting 1994).

Dualplan uses a Model II linear programming formulation to define the forest planning problem (Johnson and Scheurman 1977) and uses lagrangian relaxation search techniques and duality theory to decompose and solve the problem (Howard M. Hoganson and Rose 1984). The forest-wide problem decomposes into stand-level subproblems that are connected to each other via the dual variables associated with the forest-wide constraints of the main (master) problem.

Each subproblem uses the estimated values of dual variables for the forest-wide constraints of the master problem to recognize the stand-level impacts of stand management decisions on the forest-wide constraints. Once Dualplan develops an initial forest-wide schedule, the schedule is summarized with those results used to help re-estimate the optimal values of the dual variables for the forest-wide constraints. The subproblem solution process is
repeated iteratively, each time updating estimates of the dual variables (shadow prices) for the forest-wide constraints. With its ties to duality theory, the solution process always produces optimal solutions, yet the solutions are infeasible in that they typically violate at least some of the forest-wide constraints of the master problem. However, the process of using the intermediate results to help re-estimate the values of the dual variables is key to help move solutions towards feasibility.

Dual variable value estimates are central for addressing forest-level constraints in stand-level analyses. Essentially, each dual variable value estimate is an added bonus or penalty to include in all the stand-level analyses so that the forest-level constraints are achieved. The level of these bonuses or penalties is often valuable information to decision-makers in selecting appropriate constraint levels (targets) for the forest-level constraints, as they each represent marginal cost estimates of their associated constraint. Dualplan emphasizes the economic interpretation of the dual formulation of the forest-wide problem, which has been emphasized as valuable information for decision-makers in planning (Paredes and Brodie 1988, 1989). DTran uses current estimates of the dual variables for the forest-wide market destination constraints to make market destination decisions for stand-level harvests. As dual variable value estimates change for the timber markets in the solution process, the procurement zones for markets adjust accordingly to reflect the best market shipment decisions for the stands.

d) Integration of Uncertain Futures into the Forest-Level Model

The stand-level scenario tree that includes the forest-wide uncertainty nodes i.e. Figure 3.2 is then to be incorporated into the landscape-level model (DTran). Figure 3.3 summarizes the algorithm used to solve this stochastic forest-wide planning model.

We first read the input data and the estimates for the shadow prices, i.e.: the dual variables associated with each of the forest-wide constraints. Each stand type is subdivided to recognize stand differences in terms of the proportion of the stand that is in a riparian area, with that proportion affecting the benefits and costs of management choices. Each stand
type has an assumed location and a set of regeneration options. Each stand type can also be subdivided to represent the first time (period) available for harvest with some portions potentially not available for harvest in any period. Delays in availability are assumed to depend upon forest ownership, forest cover type, site index, and stand age.

Once the stand-level decision trees have been solved, we sum the flows of each forest level constraint and determine whether the flows are within satisfactory limits (in this case defined as 1% deviation from the target). If they are, we stop the process. If they are not, the results of the latest solution are used to re-estimate the shadow prices for each possible future and period. These values are used to return to step two and start a new iteration. After each iteration, a routine checks for potential violations of the basic rules of duality theory (Bertsimas and Tsitsiklis 1997).

![Algorithm Diagram]

Figure 3. 3 The algorithm used to solve the stochastic forest planning model for the test cases.

3.3. The Test Cases

a) Scenario Trees: Impact of the Timing and Number of Stages and Branches
To better understand the impact of the discrete definition and simplification of uncertainty we developed a set of scenario trees to test and compare. Our interest is to understand the impact of using different simplified scenario trees while keeping the underlying problem unchanged. The intent was to vary the number of stages, the number of states on the stages, and the timing of the realization of the uncertainty (the length of the stage). With the modeling results, we try to answer: 1) What are the impacts on modeling results if we assume that more information on climate change impacts unfolds sooner (5 years) versus later (20 years)?; and 2) What should forest managers be doing differently today to better prepare for an uncertain climate change future?

We first considered uncertainty trees with eight possible growth and yield scenarios due to climate change. We varied them to compare the implications of a short-term, mid-term, or long-term realization of the uncertainty. Figures 3.4 and 3.5 show the five different uncertainty trees considered.

We first defined a scenario tree with four stages. We call it “(2x2x2) early” (Figure 3.4a), reflecting that the decision tree has three realizations of the uncertainty. For each chance node, there are only two branches (two possible outcomes at that point in time) and the timings of the realizations occur “early” in the planning horizon. This scenario tree assumes we learn more about climate change impacts earlier and we can respond to the new information earlier. In this case, we learn about the future at three points in time during the first half of the planning horizon. It is also assumed that the model is deterministic for each future after the last realization of the uncertainty that occurs at the end of planning period six (Figure 3.4a).

The “(2x2x2) late” scenario tree (Figure 3.4b) is similar to the aforementioned, differing only in later realizations about climate change. Thirdly, the “(4x2)” test case (Figure 3.4c), assumes early realizations about climate change occurring only at two points in time. In this case, more information is learned when the future unfolds the first time, i.e. the first stage ends with four chance branches instead of two.
Figure 3.4 Scenario trees with eight futures at the end of the planning horizon, (a) the “(2x2x2) early” test case, (b) the “(2x2x2) late” test case, and (c) the “(4x2)” test case. The first node, the empty dot, represents time 0. Each planning period represents 5 years.

The other two of the five cases consider 16 futures (Figure 3.5). The intent of these cases is to help understand the gains from recognizing more futures. The hypothesis is that the more scenarios are incorporated into the scenario tree, the better the model will approximate the entire probability space (Kaut and Wallace 2007). Nevertheless, the cost of including more scenarios is directly related to the computational challenge of solving the stochastic programming model, which rapidly increases with the number of scenarios. These two last test cases are called “(4x4)” and “(4x2x2)”. Naming conventions are as described above, with “(4x4)”, Figure 3.5a, having three stages with each of the first two stages ending with a chance branch node with four branches. The “(4x2x2)” case, Figure 3.5b, has three realizations about uncertainty with four branches in the first realization and two branches at each of the additional chance nodes.
Figure 3. 5 Scenario trees with 16 scenarios at the end of the planning horizon, (a) the “(4x4)” case, and (b) the “(4x2x2)” test case. The first node, the empty dot, represents time 0. Each planning period represents 5 years.

Each of the futures and planning periods has a yield factor associated with each stand type. The yield factor estimates the percentage difference in yield due to climate change at that specific point in time, for that particular forest type, stand age, ecological region, and site quality. The probability associated with each chance branch indicates its likelihood. The first time the uncertainty is revealed and there is a learning event (Figure 3.6a) the multiplier of the upper (lower) uncertainty node is calculated as the expected value of the upper (lower) cone showed in Figure 3.6a. Figure 3.6b shows the distribution of the mini cones used to calculate the expected values of the yield multipliers after the second learning event, with only four possible scenarios at that period. Lastly, Figure 3.6c shows the distribution of the expected values used to estimate yield multipliers when there are eight possible scenarios.
Before solving any of the stochastic formulations, we defined three deterministic cases varying the climate change assumptions concerning the growth of aspen stands: (1) an optimistic case, (2) a pessimistic case, and (3) the average case. The optimistic (pessimistic) case used the maximum (minimum) yield multipliers for each stand. The average case used multipliers that are the expected value of multipliers overall assumed climate change futures.

b) The Minnesota Situation
We tested the model on a statewide application in Minnesota. We included all forestlands North of Cambridge (Minnesota), about 95% of the total forestland. Forests in Minnesota are very diverse in terms of forest cover types, site quality, and ownership.

Data needs were intensive and included forest inventory data, forest inventory projections, cost estimates of silvicultural treatment options, timber premiums paid for specific tree species and product classes, and timber transportation cost estimates to major timber market centers in Minnesota. USDA Forest Inventory and Analysis (FIA) inventory data was used to define analysis areas (stand types). The sampling design of the FIA plots allows them to be further divided into ‘conditions’, meaning that a proportion of a plot could differ in terms of forest cover type, ownership, stand age, or reserve status (O’Connell et al. 2016). We further subdivided each FIA plot condition to reflect estimated areas in one of three riparian classes. Furthermore, each FIA condition class was also partitioned into up to five categories to reflect different assumptions of landowner behavior related to the timing regarding the availability of timber for harvest. These availability assumptions generally varied by ownership, forest cover type, and stand age (Hoganson et al. 2017).

Likely, the best way to estimate the change in growth and yield over time produced by a changing climate would be by using a process-based growth and yield model. Empirical growth models, based on past inventories, are not suitable for estimating growth under different climate conditions from those observed during the period for which the plots were measured (Landsberg and Waring 1997). Nonetheless, process-based growth models are based on physiological processes controlled by climatic and edaphic factors that may help overcome this limitation of the empirical growth models. Even though there is a long and successful history of developing growth and yield functions for all the forest cover types in Minnesota, at this point there is no process-based model that can be used for this study.

A second possibility would be using transfer functions (Pukkala and Kellomäki 2012), use a set of correction factors to modify the existing empirical growth projections. Factors are determined as the ratio of the change in growth under climate change (using a process-based model) and the current climate.
We followed a similar approach, using correction factors that are species-specific and depend on time, age of the stand, ecological region, site quality, and assumptions about general climate change impacts. These factors are set at the forest level, representing the impact of climate change on current yield table estimates. Two stands of the same forest cover type and the same age, located in the same ecological region and with the same site index will have the same factor multiplier. The multipliers were developed using qualitative research on climate change in Minnesota. The authors understand that this is an assumption that needs to be compared with a different set of multipliers to see the sensitivity of the parameters.

The forest planning problem presented in this paper assumes the objective of maximizing expected net present value, subject to the solution being feasible under all assumed climate change futures. There is a strong interest in the potential future growth of the forest industry in Minnesota, and all of our test cases allowed for some potential expansion of the forest industry in Minnesota. Current statewide harvest levels are approximately 3 million cords but we broadened the constraints associated with the statewide level of all the tree species volume to allow for possible expansion of the forest industry. Annual harvest levels are constrained to be between 3 million cords and 4.2 million during the first period (five years), and between 3 and 4.5 million cords for the rest of the planning periods. We also use another volume constraint, associated with the volume of aspen harvested each period. This constraint sets a lower bound of 1.4 million cords, an approximate estimate of the current aspen harvest volume of recent years. For all the cases, we used a 100-year planning horizon with 5-year periods and a 4% annual discount rate.

3.4. Results

a) Comparison among Deterministic Approaches

It is helpful to compare the shadow price estimates for the volume constraints associated with all the species by planning period for the three deterministic approaches (Figure 3.7).
During the first half of the planning horizon, these shadow prices are negative, acting as penalties to maintain lower timber flows. These values increase over time, eventually becoming zero for the rest of the planning horizon. This pattern reflects the initial financially overmaturity of the forest. A steady decrease in penalties over time adds incentive to delay harvests until later periods. Specifically, reductions in penalties over time offset stand-level volume growth rates that are below the interest rate for a large percentage of the forest that is older and slow-growing in early periods of the planning horizon. The pattern across the three different deterministic model runs is very similar. The shadow price penalties associated with the most pessimistic test case are slightly and consistently lower (closer to zero) for the first half of the planning horizon. This generally implies that under the most pessimistic case there is less concern about exceeding the 4.5 million cord maximum limit and therefore the penalty to encourage delayed harvests is lower. For all cases in later periods, there is no real concern about the all-species timber flow constraints, as over time the forest moves closer to a fully regulated.

Figure 3. 7 Shadow prices ($/cord) by period for the timber harvest volume constraints of all the species for the three deterministic cases.
Differences in results for the determinist cases are prevalent in the shadow price estimates associated with the aspen volume constraints (Figure 3.8). For the most optimistic and average cases, shadow prices were zero during the first 12 planning periods. Those prices slightly increased in those scenarios between periods 14 and 19. On the other hand, the shadow prices of the most pessimistic case substantially increased after period four reaching a value of $329.4/cord at the end of the planning horizon. These differences between test cases imply that achieving the aspen volume target (1.4 million cords) would certainly be difficult to sustain throughout the planning horizon under the most pessimistic case.

Another big difference among the deterministic cases is the number of acres of the aspen forest cover type older than 80 years at the end of each planning period (Figure 3.9). The average and the most optimistic cases have the same pattern, increasing the number of acres of old aspen throughout the planning horizon and reaching their maximum during the last four planning periods. However, the most pessimistic scenario behaves differently with a
considerable deviation from the other two deterministic cases. This suggests that to achieve the minimum aspen harvest volume level in each period it needs to harvest more acres of aspen over time, due to the change in growth surrounding climate change. It is helpful to note that approximately 435,000 acres of the aspen forest cover type are assumed unavailable for harvest, with all of those acres finally over age 80 by the end of period 16 where the graphs plateau (Figure 3.9). Differences between the most pessimistic and the most optimistic scenarios are largest at the end of the planning horizon, but it is already noticeable in period 1, implying that forest management decisions and strategies would be different in the short term for each of these cases.

![Figure 3.9 Acres of aspen older than 80 years at the end of each planning period for each deterministic test case.](image)

b) Uncertainty and Aspen Harvest Level Constraints

As we mentioned earlier, one of the main goals of the study was comparing a set of scenario trees describing how uncertainty about the future may unfold (realizations). We modeled five different scenario trees as five separate test cases (see Figures 3.4 and 3.5).
There is a general pattern in the results regarding the volume of aspen harvested across all uncertainty test cases. The volume of aspen harvested is very high during the first and the second periods, over 2 million cords (Figure 3.10). This result relates to the economics of the problem. The model harvests as much as it can of the valuable, financially mature timber during the first periods to increase the net present value. This result could seem at least somewhat contrary to the strategy of holding aspen at the beginning of the planning horizon to have enough aspen for later periods. Aspen is a short-lived species and much of the aspen forest cover type is currently at a stand age where merchantable stand volume is declining. If not harvested, these stands will succeed in other forest cover types. Therefore, some of those aspen stands likely need to be harvested to keep acres as aspen cover type to help satisfy the aspen timber constraint in later periods. An additional reason for this result is that the rotation age of the aspen cover type is 40-50 years old, depending on the site index. Harvesting more acres of aspen at the beginning of the planning horizon makes it possible to fit three rotations of aspen within the 100-year planning horizon. The model values ending inventory using the shadow prices for the last planning period, with those high values at the end of the planning horizon also likely helping to incentivize the model to keep acres in the aspen forest cover type in timber production. Figure 3.10 shows the volume of aspen harvest at each period. We presented the results of the volume of aspen only for one decision tree, the “(4x2)” test case, as an example because the behavior throughout the planning horizon of the rest of the test cases was very similar.

After period two, the flow of aspen decreases and remains very close to the minimum, 1.4 million cords, until period eight. In period nine, ten, and eleven, aspen harvest levels are well above the minimum, reaching over 2 million cords, on the most optimistic futures, in period 11. This is due to the second rotation of aspen. All the acres that were harvested in periods one and two are available to be harvested again. As expected, differences in the aspen flows exist between test cases and across scenarios within each test case.
Within the stochastic test cases, the more pessimistic the uncertainty scenario is the harder it is to meet the aspen demands, as the shadow price estimates associated with these constraints need to increase substantially over time to incentivize holding some aspen for later periods (Figure 3.11, 3.12, and 3.13).

Results from the “(2x2x2) early” test case show differences in terms of the shadow price associated with the aspen volume constraints across futures (Figure 3.11). The most pessimistic future shadow price estimates increase considerably, reaching $169/cord in period 20 (Figure 3.11).
Figure 3.11 Shadow prices ($/cord) associated with the aspen constraints across the eight scenarios for the “(2x2x2) early” case.

Shadow prices across scenarios are close to zero until period 11 in the “(2x2x2) late” test case, with the exception of the most pessimistic scenario which has a positive shadow price in period six (Figure 3.12). After period six, shadow prices increase, become positive, and start growing substantially for scenario seven and eight, the two more pessimistic possible futures. Shadow prices for the most pessimistic possible future in the “(2x2x2) early” test case are higher than this test case throughout the planning horizon, with the exception of period 20 where they are approximately the same.

The volume of aspen harvested satisfies the 1.4 million cord constraint for all the periods and futures, but shadow prices for scenarios seven and eight have increased their values, achieving a maximum of $170.5/cord in period 20 and scenario eight.
Differences in aspen flow across scenarios in the “(4x2)” alternative are small during the first half of the planning horizon. In addition, shadow price estimates remain very close to zero until period 11 for all the scenarios considered but for the most pessimistic one (scenario eight). Shadow prices for the most pessimistic scenario become positive in period five, which coincides with the second time there is a learning event about the future. From that period until the end of the planning horizon, the shadow price for the most pessimistic scenarios keeps increasing until it achieves its maximum of $187.1/cord at the end of the planning horizon (Figure 3.13).
Figure 3. 13 Shadow prices ($/cord) associated with the aspen constraints across the eight scenarios for the “(4x2)” test case.

Among the three test cases considering eight futures the “(4x2)” test case is the one with a higher impact on aspen shadow prices on its most pessimistic scenario, while the other seven possible futures remain very similar across the three cases. This implies that if scenario 8 unfolds it will be very complicated to sustainable achieve the aspen target in the long term. This fact can also be observed in the acreage of old aspen for the “(4x2)” test case, with fewer acres on scenario seven and eight, in comparison to the other two cases.

On the other hand, the two test cases with 16 scenarios behaved in a different way. Aspen shadow prices throughout the planning horizon show the same general pattern as the cases just presented, but their values are much higher, reaching values such as $288.6/cord at the end of the planning horizon (Figure 3.14). In terms of volume of aspen harvested, the “(4x2x2)” test case presents the same general pattern as the behavior of the test cases with eight futures but also shows some difference. In period two, this test case already shows a difference in volume harvested by possible future, harvesting more aspen volume as the future is most pessimistic. This is linked to the idea that in order to achieve the target of
aspen volume at the end of the planning horizon it needs to harvest more aspen on the earlier period and be able to fit three rotations of aspen in the planning horizon.

Figure 3. 14 Shadow prices ($/cord) associated with the aspen constraints across the 16 possible scenarios for the “(4x2x2)” test case.

There are not many differences between these two test cases with 16 possible scenarios. We can find three different behavior across their possible 16 futures. Futures from one to 11 tend to perform very similarly, both in terms of shadow price estimates and in terms of the volume harvested. The second group would include futures 12 to 15, which also show a similar pattern across them but different from the previous one. Lastly, the most pessimistic future, future 16, shows the highest shadow prices and lowest aspen volume harvested throughout the planning horizon.

c) Acres of Aspen Harvested and Acres of Old Aspen (> 80 years old)

Some differences were found in the aspen cover type. Regarding the acres of aspen harvested by period, we observed there is a gap between the most optimistic and most
pessimistic scenario. Figure 3.15 shows the acres of aspen harvested by period, on each possible future for the “(2x2x2) early” test case. The difference between those two futures is close to 80,000 acres in period eight but we start seeing some differences already in period two. Across test cases, the “(2x2x2) late” and “(4x2)” test cases showed similar behavior to the one showed in Figure 3.15.

Acres of aspen harvested are very high during the first two periods (Figure 3.15). This corresponds to the elevated volume harvested in those periods. In period three, they drop to increase again in period four. After period five, the acres of aspen harvested increase again to reach the maximum in period 11, when the second rotation of aspen occurs.

There is an identified pattern across test cases. Within each test case, the most pessimistic possible scenario harvests more acres than the most optimistic one. This fact might be due to two reasons. Impacts on growth surrounding climate change are higher in the most pessimistic scenario than in the most optimistic, which means that the reduction of aspen growth in future eight will be higher than in future one. In order to achieve the 1.4 million cord target throughout the planning horizon, there will be a need to harvest more acres under scenario eight. The relatively higher level of acres harvested under scenario eight in the later periods of the planning horizon raises questions about whether this same level could be sustained beyond the end of the planning horizon when such a level would almost certainly be needed to sustain the 1.4 million cord harvest target for scenario eight. Furthermore, the idea of keeping more acres of aspen as an aspen cover type instead of losing them and letting them succeed in other cover types has an influence over these results too. The pattern observed on the two 16-future test cases is very similar to the ones with eight possible futures, having slightly more acres of aspen harvested in the most pessimistic scenario throughout the planning horizon.

This idea can also be observed in the acreage of old aspen (> 80 years old) left at each planning period across decision trees (Figures 3.16 and 3.17).
Figure 3. 15 Acres of aspen forest cover type harvest by period under each possible future scenario.

Generally, across test cases and across possible scenarios on each test case, the acres of aspen older than 80 years old increase through time until it reaches the maximum, in period 16, and then it remains constant until period 20 (Figure 3.16). The case study includes acres of forestland reserved from harvest and all of these acres reach the older-than-80-years-old condition by the end of period 16.

Another common behavior across test cases is the difference in the number of acres of aspen older than 80 years between the most optimistic and the most pessimistic scenario within the same test case. The most pessimistic future leaves fewer old aspen acres by period than any other future for each test case. The intuition for this behavior aligns with what we explained earlier. The most pessimistic scenario needs to harvest more acres of aspen to achieve the aspen volume constraint on each period.

Table 3.1 shows a comparison of older aspen across test cases at the end of the planning horizon. There is a slight difference between test cases with eight possible scenarios and the 16-scenario test cases. In general, the 16-scenario test cases show a lower amount of old aspen remained in the landscape in period 20 for the most pessimistic scenario. Among
the 8-scenario test cases, there are also some differences. When the impact of climate change on growth is recognized to be happening earlier ("(2x2x2) early" and "(4x2)"") the amount of old aspen remaining on the landscape at the end of the planning horizon is significantly less than the "(2x2x2) late". This reflects that the model is also adjusting to climate change earlier, thus needing to harvest more acres earlier to compensate for the lower yields per acre associated with the more pessimistic scenarios. Essentially the “2x2x2 late” test case is allowed to use an average future for yield multipliers until its uncertainty tree first branches at the end of period four.

Table 3. 1 Acre of aspen older than 80 years at the end of period 20.

<table>
<thead>
<tr>
<th>Test cases</th>
<th>(2x2x2) early</th>
<th>(2x2x2) late</th>
<th>(4x2)</th>
<th>(4x2x2)</th>
<th>(4x4)</th>
<th>Deterministic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most optimistic</td>
<td>744,968</td>
<td>730,414</td>
<td>741,316</td>
<td>747,985</td>
<td>744,177</td>
<td>745,682</td>
</tr>
<tr>
<td>scenario</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Most pessimistic</td>
<td>551,184</td>
<td>614,260</td>
<td>537,196</td>
<td>503,788</td>
<td>516,919</td>
<td>467,268</td>
</tr>
<tr>
<td>scenario</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. 16 Acres of aspen older than 80 years old left at the end of each planning period across the eight scenarios for the “(2x2x2) late” test case.
3.5. Discussion

Incorporating uncertainty into the forest planning process is certainly a challenge and a complex task. We discuss briefly a few insights from our experiential learning associated with the development of this multi-stage stochastic forest planning model that may be helpful for other studies.

a) Benefits of Considering Uncertainty versus a Deterministic Forest Planning Model

When planning using a deterministic approach, we first face the question of which perspective the manager should adopt when defining the forest planning problem. Should we manage for an optimistic or pessimistic scenario? What about an average scenario? Results show that planning for the average deterministic case is far from being the average solution of the most pessimistic and most optimistic scenarios. For our large and detailed statewide test cases, the solution of the average deterministic test case is very similar to the most optimistic assumption. Planning for an average deterministic case will likely produce a misleading solution, minimizing the potential impact of climate change. On the other
hand, the most pessimistic test case results in unsustainable harvest levels and unrealistic prices for the aspen cover type in the long term. Considering uncertainty emphasizes finding a solution that performs well under all the scenarios.

b) Benefits of Using One Uncertainty Tree over another One

As shown in the results, the discrete uncertainty tree used to solve the problem has an impact on the solution. In terms of the aspen cover type, the harvest levels were hard to satisfy for some of the scenarios for the 16-scenario test cases, reaching very high shadow prices and still violating the aspen volume constraints for several time periods. For the 8-scenario test cases, the pattern of both shadow prices and volume harvested showed that the sooner the uncertainty unfolds or the more information we are able to learn at that point (four branches versus two) the sooner that management can or needs to adjust. In addition, a later branching implies planning for an average yield change during the short-term and thus potentially under-estimates the potential effect of climate change.

Results show that there is not much impact of the test case used to achieve the constraints associated with the volume of all the species, producing similar harvest levels and shadow price patterns. This could be due to both the current conditions of the forests and the somewhat wide window between the lower and the upper bound used to define these constraints. Results from initial tests helped guide and refine the tests presented in this paper. Initial runs had different bounds on both the aspen and the all-species volume constraints. Bounds on the constraints of the volume of all species were initially between 4 and 4.5 million cords. That harvest level is very high compared to the current level in Minnesota. We wanted to keep the problem as realistic as possible and decided to drop the lower bound to 3 million cords and keep the upper bound. Both the volume harvested and the shadow prices associated with those constraints indicate that achieving these constraints is not difficult to satisfy under all the test cases presented and across all the scenarios.
c) Harvest Levels: Are Even Flow Constraints Suitable for Uncertainty?

The use of constant aspen prices showed some limitations. Some of the results indicate that the aspen volume constraints would not be sustainable long term when facing growth and yield uncertainty surrounding climate change. The intuition tells us that the harvest level could be increased or decreased depending on the uncertain outcome, increasing the flexibility, and preparing for a range of possible futures. The use of a downward sloping demand curve could likely help overcome those challenges.

The fixed price per unit of the output regardless of the amount of volume produced on each period implies a horizontal, perfectly elastic demand curve. When the producer’s output is large enough to affect substantially the market price, the assumption of a fixed price would not be valid. It would likely be more realistic to use a downward sloping demand curve for aspen timber in the face of uncertainty.

This will be the focus of the next chapter: addressing the combination of downward sloping demand curves for timber and the forest-wide uncertainty related to growth and yield surrounding climate change.

d) Considering Additional Assumptions, Data Needs, Additional Sources of Uncertainty and Further Analysis

Including site conversion or natural succession options of stands to other forest cover types after harvest will likely have an impact on the results. Our scenarios currently assume that the forest cover type on each stand type does not change over time. Adding site conversion options will substantially increase the size of the stand-level decision tree, due to the bare land nodes available after harvest. However, site conversion options could be limited to stand types that are most likely to benefit from conversion. Unfortunately, information about which cover type will adapt and grow better under different scenarios of climate change is certainly not clear at this point.
Inventory scheduling would be another strategy that could likely help address uncertainty. Inventory measurements throughout the planning horizon will certainly add information about the changes in growth and yield that occurred between those periods, helping us learn about the impact of climate change on the growth and yield throughout the planning horizon. It may be helpful during each inventory period to concentrate some forest inventory measurement efforts on some subset of the forest where results would likely have impacts on needed immediate management decisions. Essentially, if a stand is measured, then the forest management decision could be made with better information about its existing condition including potential recent climate change impacts on those conditions. It would be interesting to further explore the integration of inventory scheduling and multi-stage stochastic management planning as future work. It might be a way to collect more information that could add extra value to the forest management decision making when addressing uncertainty surrounding future growth and yield. In our simple forest-level uncertainty trees we assume that new information becomes available only two or three times over a 100-year planning horizon. Deterministic harvest scheduling models assume no new information over the entire planning horizon.

As mentioned earlier, the nature of forest planning problems encompasses several sources of uncertainty. There is still a lack of understanding about how climate change could affect forest ecosystems and how soon such changes could occur. Among the effects of climate change on forests, we are very likely to see changes in the future growth and yield of different species; changes in regeneration, mortality, and competition between species; alterations of the intensity and frequency of catastrophic events; and loss of biodiversity. A changing climate might also produce socioeconomic impacts, as well as variation in market prices, interest rates, taxes, and forest landowners’ behavior. An obstacle in taking uncertainty into account in the forest planning process is certainly the integration of different sources of uncertainty and the knowledge of the interactions between them. This is also a topic that the authors consider important and worthy of future research.
3.6. Conclusions

In this chapter, a multi-stage stochastic model was developed that takes into consideration the forest-level uncertainty of growth surrounding climate change into the forest planning process. Although this approach was used to address the uncertainty related to growth and yield due to climate change, the model is valid to solve other sources of uncertainty at the forest level.

Simplified forest-level scenario trees were developed to describe uncertain future forest-level growth and yield conditions. These alternative scenario trees were compared in terms of their impact on planning when using a proposed multi-stage stochastic harvest scheduling model. Tests assumed the same forest-level uncertainty at the start of the planning horizon for all scenario trees. Comparisons of model results show that the sooner that this uncertainty is revealed or the more information that is learned when it is revealed then the sooner stand-level management can be better tailored to fit with the forest-level conditions of the future.

A big advantage of the proposed modeling approach is the decomposition method used to solve the master problem. By recognizing the forest-level uncertainty directly in separable stand-level problems, the model can successfully be applied to a very large area, and at the same time, recognize substantial detail in the many stand-level analyses. Furthermore, due to this decomposition approach, the master problem was solved taking advantage of parallel processing, distributing the task of solving individual sub-problems into different processors that can be solved independently.

The use of a downward sloping demand curve for aspen could help mitigate some of the infeasibilities produced under some test cases with a fixed price (horizontal demand curve) and a lower bound of 1.4 million cords per year.
Chapter 4: Integrating Climate Change Uncertainties with Price-Sensitive Timber Demands for Developing More Resilient Landscape Management Plans

4.1 Introduction

As mentioned in Chapter 3, the nature of forest planning problems encompasses several sources of uncertainty. From all the potential sources, addressing the impact of climate change on forests is considered to be a priority. A change in precipitation patterns, as well as an increase in temperature and atmospheric CO2 levels, will presumably have major ecological effects on forests and economic impacts on the forest sector. There is still a lack of understanding about how the changing climate could affect forest ecosystems and how soon such changes could occur. Climate change is clearly a critical challenge that forest managers face nowadays; forests are a crucial global source of both valuable market goods and environmental benefits (Sedjo and Sohngen 1998). Among the effects of climate change on forests, we are very likely to see changes in the future growth and yield of different species; changes in regeneration, mortality, and competition between species; alterations of the intensity and frequency of catastrophic events; and loss of biodiversity.

A changing climate might also produce socioeconomic impacts, as well as variation in market prices, interest rates, taxes, and forest landowners’ behavior towards how to manage their land.

All the aforementioned potential changes will likely be area-specific and each particular location will be prone to facing different challenges. Results of recent modeling studies projecting expected temperatures under climate change simulations indicate that there might be a positive influence on the global forest sector, increasing global timber supply while maintaining and potentially reducing timber prices (Kirilenko and Sedjo 2007). However, forests in many locations will need to deal with certain local challenges linked to climate change. In Minnesota, forests are considered very diverse. They include three of Bailey’s ecosystem provinces: Oak Prairie Parkland in the west, the Eastern Deciduous
Forest through the center and southeastern section, and the Laurentian Mixed Forest in the northeast (Bailey 1983). It is exactly on the fringes of those biomes where attention should be most intensely placed. A warmer climate will have strong impacts on boreal and northern hardwood forests, located in the vicinity of the boundary of the prairie-forest biomes. It is expected that global warming would produce a shift of the prairie-forest border of central North America towards the northeast. This shift could consequently lead to the loss of a substantial area of existing forestland that may transition to savannas or grasslands (Frelich and Reich 2010). This is of importance for forest managers and stakeholders in Minnesota and therefore a forest planning approach that places substantial details into recognizing the differences between the impact of climate change across ecological subregions would be crucial.

A multi-stage stochastic model that helped understand how the uncertainty surrounding growth and yield due to climate change was developed in the previous chapter. One of the observations and conclusions of that chapter is in relation to the periodic forest-wide volume constraints for the aspen volume. Constraints are a priority in an optimization problem because all the constraints in the model need to be satisfied regardless of the objective function value. In forestry, forest-wide constraints can be associated with area or volume of timber harvested in each period, limitations in the budget for different activities, or related to ecological values or carbon sequestration targets among others, but they are usually included to move the forest toward the desired future conditions.

Often times, forest planning models use either horizontal or vertical demand curves for goods and services. A demand curve defines the relationship between the price of a good or service and the quantity demanded in a given period of time. In one extreme, a vertical demand curve will constrain the problem forcing it to obtain a fixed quantity from the forest regardless of price. On the other extreme, a horizontal demand curve would represent the case where the amount of output or condition is always valued with the same per-unit price, regardless of the amount of output produced. These two cases were explored and applied to environmental values in Chapter 2.
A potential alternative is to use a downward sloping demand curve in the formulation. This demand curve recognizes that the per-unit marginal value of a forest output or condition is higher when the output or the condition is scarce. This concept is interesting when used for addressing both an environmental condition, (De Pellegrin Llorente et al. 2018), or timber market flows, as we will see in this chapter because it helps recognize the sensitivity of demand to price.

Walker (1976) emphasized the use of demand curves in his Economic Harvest Optimization model. It showed that using price/demand relationships will move the forest towards a more balanced age class distribution without the need of using even-flow constraints. The implementation of a downward sloping demand curve into a forest planning model can be added easily using a piecewise linear approximation of the objective function and a constraint to define the harvest level for each price step (Hrubes and Navon 1976).

A strategy to potentially deal with uncertainty in forest planning is to increase flexibility and keep the options open, to be able to adapt to several futures. In Chapter 3, constraints associated with the aspen volume were defined using a horizontal demand curve in combination with a lower bound (1.4 million cords). When the realization of the climate change happened sooner in the planning horizon, the model produced some infeasibilities, suggesting that it would be unsustainable to satisfy the constraint in the long term. A more resilient forest management plan would be the one that can adapt to different future scenarios, making management decisions dependent on how the future unfolds. (Boychuk and Martell 1996b) explored the combination of a multi-stage stochastic model to account for the uncertainty associated with fire losses with a downward sloping demand function for timber production. Results of their study showed that both test cases, with and without using a downward-sloping demand curve, produced a similar trend of the volume of timber harvested, but adding a downward sloping demand curve helped reduce the high and low extremes of the quantity of timber harvested.

The main goal of this chapter is to explore the idea of the combination of downward-sloping demand functions for the periodic aspen harvest volume and the multi-stage
stochastic forest management model presented in Chapter 3. The intent is to compare multiple cases to analyze the impact of considering a different demand function associated with the aspen volume at the same time as the model addresses the uncertainty associated with the growth and yield due to climate change. This will help better understand the tradeoffs of different forest management strategies. A sensitivity analysis concerning the growth and yield multipliers used to define the impact of climate change is also conducted in this chapter.

4.2 Methods

We use the forest management planning model developed in the previous chapter and applied it to a test case. Each of the forest-wide scenario trees defined in Chapter 3 (Figures 3.4 and 3.5) presents some advantages/disadvantages and produces different solutions to the model. In this chapter, only one decision tree will be considered and it will be used to test multiple cases to address a different demand curve. The forest-wide uncertainty decision tree chosen for this chapter is the “(2x2x2) early” test case (Figure 4.1). The reason behind this decision was to select a decision tree whose impact of the change in growth and yield occurred earlier in the planning horizon.

The model will be applied to a study case in Minnesota. The reader is referred to the specific sections of Chapter 2 and Chapter 3 for an overview of the forest management situation in Minnesota.
a) Demand Curve Scenarios for Aspen Volume Constraints

For the stochastic forest planning model developed in Chapter 3, each volume constraint assumed a constant price. In the case of the all-specie volume constraints, there were two additional constraints, a lower and an upper bound, limiting and penalizing the volume of timber harvested outside those two ranges. In the case of the aspen constraints, the model assumed a constant price and it used at the same time a lower bound constraint on the aspen volume harvested. For these constraints, there is no penalty associated with harvesting more timber than the lower bound. The price for aspen does not change according to a demand curve, it is maintained constant, giving to the model the option of harvesting large volumes in any period without any penalty.

Substituting a downward-sloping demand function for the fixed-price demand curve used in Chapter 3 will give the model the flexibility of finding the price/quantity equilibrium in each period. Consequently, periods with low volume are rewarded with a higher price, and periods with a high volume are penalized with a lower price, without the need of using the lower bound constraint on the aspen volume that was used in Chapter 3.

We assume that the type of demand curve used will certainly have an impact on how the model behaves. The steeper the downward-sloping demand function the greater the penalty.
or the reward is given to a certain change in that good or service. The flatter the curve, the closer to the fixed price strategy that was used in Chapter 3.

For testing purposes, two sets of downward-sloping demand curves were defined hypothetically (Figure 4.2). The intent is to cover two different situations, steeper curves, and flatter curves.

Each of the demand curves in each set shown in Figure 4.2 varies by period, meaning that on each test case a single demand curve is assumed for all the aspen volume harvested in a given period. For earlier periods, curves are steeper reflecting that production levels are less responsive in the market to price in the near term.

On the other hand, the same curve is used regardless of the ecological region, ownership, and the demand of each mill where the output product will be delivered. A much deeper study would be needed to gather all that information.

b) Additional Test Cases

Aspen is one of the main forest cover types and with the highest demand in Minnesota. It is also widely spread throughout the state and it usually contains a considerable component of other species, with the mix of other species generally varying across the study area. The
forest planning model recognizes important details regarding stand-level differences in the cover type, such as stand age, ecological region, site quality, riparian percent, and distances to timber markets. Moreover, we defined additional test cases to help understand the behavior of the aspen cover type under different conditions.

Recognizing the importance of aspen harvest levels, we considered an additional modification to the model related to the amount of timber of aspen harvested each period. We saw in the results of Chapter 3 that the amount of aspen harvested at the beginning of the planning horizon was over 2 million cords. Aspen harvest levels in Minnesota have approximately been 1.4 million cords in recent years. With the main goal of understanding the changes produced by limiting the aspen volume harvested, an upper bound on the aspen cover type was introduced. We defined a constraint for the aspen volume at 1.8 million cords per year throughout the planning horizon. Constraints on the statewide annual harvest levels for all species remain the same as in Chapter 3. Annual harvest levels are constrained to be between 3 million cords and 4.2 million during the first period (five years), and between 3 and 4.5 million cords for the rest of the planning periods.

Finally, an additional test case was defined to explore and understand the sensitivity of the model to the set of yield multiplier used to describe the different forest-level scenarios describing growth and yield uncertainty. The new set of multipliers was defined using the same approach as Chapter 3. Each of the futures and planning periods has a yield factor associated with each stand in each planning period and scenario. The yield factor estimates the percentage difference in yield due to climate change at that specific point in time, for that particular forest type, stand age, ecological region, and site quality. However, the new set of yield factors is considered to be more pessimistic, with slightly higher yield reductions than the baseline test case explained in Chapter 3.

4.3 Results

In summary, each test case corresponds directly with an application of the stochastic forest management scheduling model developed in Chapter 3, and each was a combination of
assumptions concerning three facets described in this methods section: (1) one of three demand functions for aspen timber volumes over time (horizontal, demand curve 1, or demand curve 2); (2) one of two options for a maximum limit on aspen volumes (with or without the 1.8 million cord upper bound for aspen); and (3) one of two sets of yield multipliers. Test cases include approximately 100,000 analysis areas, 20 five-year planning periods, seven major timber market centers, and eight climate change scenarios (futures). To calculate the net present value of all stand-level management options, a 4% annual discount rate was used for all scenarios.

a) All Species Volume Constraints

As explained before, the constraint set associated with the volume of all species by period has not been changed from Chapter 3. The general pattern of both the amount of timber harvested and its associate shadow prices remains very similar to what we saw in Chapter 3: the volume remains high, around 4.5 million cords, until period 10 or 12, depending on the future, and after that, it drops to reach a minimum in periods 14 and 15 (Figure 4.3). Then it increases again to a local peak in period 19 and it drops. However, when the downward-sloping demand curves for aspen are used, some differences are observed (Figure 4.3b and 4.3c). The main difference remains in that all the futures are clearly differentiated under both downward-sloping demand cases (Figure 4.3b and 4.3c), drawing a reverse-J shape between periods 11 and 15. Under the horizontal demand (Figure 4.3a), all the future flows are merged in period 13 and remain very close to each other until period 17. The use of a downward sloping demand curve helps smooth the up-and-down trend between periods 14 and 18 that the horizontal demand shows.

There is almost no difference between the demand-curve-1 and the demand-curve-2 test cases. The constraint associated with the volume of all the species has not been changed. Even though the results of modifying the constraint associated with the aspen volume will have an impact on the volume of all the species, in this case, is minimal.
b) Aspen Harvest Level Constraints

The volume of aspen produced substantially changes depending upon the different demand curves (Figure 4.4). A horizontal constraint produces a highly unstable flow of timber throughout the planning horizon, with very high volumes produced at the beginning and the middle of the planning horizon (Figure 4.4a). Those two peaks of timber, over 2 million cords, correspond to the first and second rotation of aspen. The flow of aspen is very close to the 1.4-million-cord constraint for the rest of the planning horizon. It is during the periods where the aspen flow peaks where differences across scenarios are found, producing a higher volume of aspen in the most optimistic scenarios.
Figure 4. Volume of aspen harvested by period (three graphs on the left column) under (a) a horizontal demand curve, (b) the downward sloping demand curve 1, and (c) under the downward sloping demand curve 2. Aspen shadow prices ($/cord) associated with the aspen volume constraint (three graphs on the right column) under (d) a horizontal demand curve, (e) the downward sloping demand curve 1, and (f) under the downward sloping demand curve 2 (Legend: see numbering of the different scenarios in Figure 4.1)
On the contrary, the aspen flow under the downward sloping demand curve 1 shows a different trend (Figure 4.4b). The maximum volume harvested occurs during the first period. Even though the price corresponding to such a high of output produced is low the economics of the problem makes it more efficient to harvest over 2 million cords during the first two periods at a lower price than postponing its harvest to a later period. After period one, the aspen flow decreases very slowly. On the second rotation, period 11, there is a slight tendency in all the futures of increasing the flow harvested, being more visible in the more optimistic scenarios than in others. Moreover, the use of the downward sloping demand curve 1 produces different flows across different futures, obtaining a range of flows depending on the future scenario. This gap between the volume harvested on the most optimistic scenario and the most pessimistic grows through time, achieving its maximum at the end of the planning horizon.

The aspen flow produced under the demand curve 2 presents a similar trend to the demand curve 1 test case (Figure 4.4c). However, the use of the demand curve 2 produces a high flow in periods 1 and 2 (close to 2 million cords) that suddenly drops to 1.5 million cords in period 3. This pattern at the beginning of the planning horizon differs from the flow produced by the demand curve 1 constraint. This was expected to happen due to the different design of the demand curve 1 and 2. Demand curve 2 assigns a lower price to higher flows. With this curve, the model picks to harvest a higher volume for the first two periods even if the associated price is lower and wait until period 3 to drop the flows drastically and achieve a higher price.

Another difference between the results of both downward-sloping demand curves is that under demand curve 2 the peak of aspen harvested in period 11 reaches over 1.9 million cords under future 1, but it is also observable under most of the futures (from 1 to 5). This pattern is much more subtle under the demand curve 1. Under demand curve 1 there is an incentive for lowering a bit the flows (price is higher for the same flow) while under demand curve 2 prices are lower and the model picks harvesting more and gets the economic benefit of harvesting instead of holding some timber for later periods.
Concerning shadow prices associated with the aspen volume constraints (the three graphs on the right column of Figure 4.4) differences across demand curves were also found. In alignment with the aspen flow, shadow prices for aspen constraints with a downward-sloping demand curve have a different pattern compared to the horizontal demand test case. The trend has changed now. The first thing to highlight is the value of the shadow prices under both downward-sloping demand curves (Figure 4.4e and 4.4f). The highest shadow price found under those two test cases is around $55/cord at the end of the planning horizon, compared to the $169/cord found under the fixed-price test case (Figure 4.4d). The always-raising shadow price pattern that we found using the horizontal demand curve is not present anymore under the other two test cases. When using the demand curve 1, we found an initial increase in prices (associated with that initial decrease in aspen flow), finding a local peak in period 8. After that period, prices slightly decrease until period 11 (the local peak we saw in the aspen flows) and they increase until the end of the planning horizon. There is a logical correspondence between the aspen flow produced in a specific period and its shadow price, defined by the price-quantity relationship (downward-sloping demand curve). An advantage of using this approach is that the impacts of a forest age imbalance are reduced due to dropping the price in periods when harvest volumes are very high.

When looking at the trend across futures within the two test cases with a downward-sloping demand function, the pattern of shadow prices is similar across futures, and in concordance with the aspen flow (high prices, lower flow, and vice versa). There are some differences in the value of the shadow price across futures, finding a higher shadow price on the more pessimistic scenarios.

c) Acres of Aspen Harvested and Acres of Old Aspen

Acres of aspen harvested are somewhat aligned to aspen flows; the more timber harvested the greater number of acres we will need to harvest to obtain that flow. The trend of the number of acres harvested in the aspen cover type by period also varies when considering a horizontal demand curve or a downward-sloping demand curve (Figure 4.5). A more
stable trend is found under the demand curve 1 test case (Figure 4.5b). There are still some ups and downs throughout the planning horizon, notwithstanding, it does not show the same high and low peaks observed in the horizontal demand curve test case (Figure 4.5a). The number of acres harvested under the horizontal demand constraint has high oscillations, and the same unsteady pattern was found in terms of volume of aspen harvested. When the demand curve 2 test case is used, the results related to the number of acres harvested show a more irregular pattern, compared to the demand curve 1 test case. As explained in the former section, demand curve 2 produced a higher flow of aspen in periods 1 and 2. That fact is visible also in the number of acres harvested during those periods (Figure 4.5c). In that sense, Figure 4.5c is more similar to the horizontal demand test case (Figure 4.5a) than to the number of acres harvested under the demand curve 1 (Figure 4.5b). The demand-curve-2 function is defined as a “flatter” curve than the demand-curve-1 function, meaning that the penalty or reward of a change in quantity is smaller under the demand curve 2 than under the demand curve 1 test case, allowing, therefore, these type of fluctuations.

Across futures, the pattern is very similar across test cases and to the one found in Chapter 3. The more pessimistic future (future 8) needs to harvest the greater number of acres to be able to produce the same aspen volume as future 1 due to the impact of climate change in the aspen yield. There are some specific periods where this is not the case, for example, period 11 because in those periods the volume of aspen harvested in the most optimistic futures was extremely high.
Figure 4.5 Acres of aspen harvested by period under (a) a horizontal demand curve, (b) the downward sloping demand curve 1, and (c) the downward sloping demand curve 2 test cases. The three graphs have the same scale in both axes for comparison purposes. (Legend: see numbering of the different scenarios in Figure 4.1)

We just explored the number of acres of aspen harvested under each demand curve, but it is also crucial to understand the impacts of the three test cases on the conditions of the forest each period. Figure 4.6 shows both the number of acres of old aspen (> 80 years old) and the number of acres of aspen between 55 and 80 years in the forest at the end of each period. The reader can get a completely different impression regarding the impact of a specific demand curve is by looking at one of those graphs independently. The graphs are presented side by side to get a full perspective on the subject.

The horizontal demand curve test case produces the widest range in the number of acres of forest over age 80 (Figure 4.6). That range increases through time being maximum at the end of the planning horizon. The behavior is the same as we saw in Chapter 3, future 1.
does not need to harvest acres to satisfy the volume constraint and the model does not pick
to harvest them. However, future 8, the most pessimistic scenario, needs to harvest more
of those acres to either meet the volume constraint or keep acres of the aspen cover type
by cutting and regenerating them, leaving fewer acres of old forest on the forest. Under the
other two downward-sloping demand test cases, the window between the most optimistic
and the most pessimistic futures is smaller. In these cases, the number of acres of old aspen
left in the forest under future 1 at the end of the planning horizon is less than the acres left
under the horizontal demand curve. This could be explained because aspen equilibrium
prices for future 1 are greater in later periods, acting as higher rewards for postponing
harvest to later periods. This incentive to keep more acres of aspen in production compared
to future 1 under the horizontal demand curve, where there is no additional incentive for
future 1 shadow prices. It is important to mention that the number of acres of aspen older
than 80 years old is accounting for the reserved acres of forestland that cannot be harvested.
That is the explanation of why those trends grow through time until they reach a plateau in
period 16. The reserved forestland is aging and being tallied on the older-than-80 category
as it ages.

On the other hand, looking at the trend of acres between 55 and 80 years old, the general
pattern is completely different. We observe a declining trend over time under the three test
cases, with some differences across them (three graphs on the right column of Figure 4.6,
i.e. Figure 4.6d, 4.6e, and 4.6f). The general pattern implies the financially over mature
current conditions of this cover type, over 1.1 million acres of the aspen cover type is
between 55 and 80 years old in time zero. It also reflects a combination of these three facts:
1) these acres are being harvested throughout the planning horizon, 2) they are growing to
an older category, and 3) there are not many acres of the younger category that are growing
and being included in this category. The forest conditions showed at the end of the planning
horizon under the three demand curve test cases, reaching some periods with very few acres
between 55 and 80 years old, is not a very desirable scenario. This age imbalance would
not allow the possibility of providing other ecosystem services such as habitat for some
wildlife species or vertical structure diversity, to list only a couple of examples.
Figure 4. 6 Acres of old aspen (> 80 years old) by period (three graphs on the left column) under (a) a horizontal demand curve, (b) the downward sloping demand curve 1, and (c) the downward sloping demand curve 2 test cases. Acres of aspen between 55 and 80 years old (three graphs on the right column) under (d) a horizontal demand curve, (e) the downward sloping demand curve 1, and (f) the downward sloping demand curve 2 test cases. The three graphs on the same column have the same scale in both axes for comparison purposes. (Legend: see numbering of the different scenarios in Figure 4.1)
The number of acres between 55 and 80 years old left in the forest under the demand-curve-2 test case is generally higher than under the demand curve 1 and closer to the results we observe under the horizontal demand curve, even though they are minor differences between test cases. What it is interesting to highlight is the change produced between periods 10 and 11. Under the horizontal-demand test case, the most optimistic future, future 1, is leaving on the forest a higher number of acres until period 10. After period 11, this trend is switched, and the most pessimistic future starts producing more acres than future 1. Under the two downward-sloping-demand-curve test cases this pattern does not occur. We observe that is always the most optimistic future that is leaving a higher number of acres between 55 and 80 years old in the forest.

d) Additional Test Cases

The impact of the upper bound defined for the aspen volume is very limited when considering the volume harvested of all the cover types, regardless of the demand curve used to define the relationship between the price and the quantity. Almost no difference was found in both the flow and the shadow prices associated with the all-specie volume constraints.

However, when adding an upper bound constraint on the aspen volume to the horizontal-demand test case, the flow of aspen harvested changed its pattern (Figure 4.7a). Due to the upper limitation of aspen on 1.8 million cords, the high flows we saw in Figure 4.4a in periods 1 and 2, over 2 million cords, have been reduced to the maximum of timber allowed (1.8 million cords) during the first four periods. As we saw in Chapter 3, the high volume of aspen harvested during the first periods is likely related to the economic facet of the problem where the model will pick to harvest the maximum amount of timber allowed by the constraints and do it sooner rather than later, to maximize the net present value.

Similarly, the peak we observed in period 11 under the horizontal-demand test case and on future 1, with a flow over 2 million cords is decreased to the upper bound and spread to
periods 10 to 12 in the upper bound test case, showing a plateau of 1.8 million cords during those 3 periods. Future 8, on the other hand, is close to the lower bound constraint on aspen (1.4 million cords) from period seven until the end of the planning horizon.

At the end of the planning horizon, in period 20, all the futures’ aspen harvests are close to the minimum constraint but future 1, which increases its flow around 1.6 million cords. This is due to the third rotation in the aspen cover type and the high flow harvested under this future in periods 10 to 12. The other futures, however, have both a lower harvest during the second rotation of aspen and likely a higher reduction in the yield multipliers due to climate change that does not allow a higher flow in period 20.

Shadow prices associated with this constraint (Figure 4.7c) show a similar pattern to the horizontal-demand test case without the upper bound (Figure 4.4d). The most pessimistic future, future 8, shows higher values with an aspen upper bound than the test case with no upper bound. The 1.4 million-cord aspen lower bound constraint is hard to satisfy in all the periods without an aspen upper limit, as we discussed in Chapter 3. When the 1.8 million-cord upper bound is added the lower bound constraint becomes harder to satisfy, needing to increase the shadow prices (reward) for that future to encourage postponing the harvest to later periods.
Figure 4. 7 Volume of aspen harvested by period (two graphs on the left column) under (a) a horizontal demand curve and (b) the downward sloping demand curve 1. Aspen shadow prices ($/cord) associated with the aspen volume constraint (two graphs on the right column) under (c) a horizontal demand curve and (d) the downward sloping demand curve 1 (Legend: see numbering of the different scenarios in Figure 4.1)
On the other hand, adding the upper bound constraint to the aspen flow has almost no impact on the downward-sloping demand curve 1. Aspen flows during the first few periods (Figure 4.7b) have slightly decreased from the over 2 million-cord flows we obtained under the Demand Curve 1 test case without an upper bound (Figure 4.4b). However, the general trend in both aspen flows and aspen shadow prices have not been changed after adding the aspen upper bound.

There are not many differences in terms of the number of aspen acres harvested. Under the horizontal-demand test case, we can observe a decrease in the number of acres at the beginning of the planning horizon and again around periods 10-12. This is aligned with the aspen flow results. With the upper bound constraint, the aspen volume harvested in those periods is lower; therefore, the number of acres harvested is also lower than the horizontal demand test case with no upper bound.

The demand-curve-1 test case with the upper bound constraint in aspen flow does not show many differences in term of the number of acres of aspen harvested or the number of acres of old aspen, compared to the baseline test case with no upper bound constraint.

Surprisingly, the test of a new set of multipliers did not show many different results in some test cases. The test case that considers a downward-sloping demand function for the aspen volume showed little changes in both aspen volume and their associated shadow prices, presenting generally lower aspen volume and higher prices. One explanation could be that the new multipliers were not as different as the initial set, producing therefore a similar result under both sets of multipliers. It might also be because, with a downward-sloping demand function, lower quantity produced results in higher prices. That means that there is some incentive to capitalize on higher prices, with lower quantities. A deeper study of this area would be needed to further answer more questions.

The biggest differences were found under the horizontal-demand curve test case (Figure 4.8a and 4.8b). With the new set of multipliers, the model takes more interactions to solve with substantially higher aspen shadow prices needed to satisfy aspen volume constraints in later periods, reaching $207/cord in period 20 for future 8. The pattern of the aspen shadow prices throughout the planning horizon remains the same but their values showed
some differences, being more noticeable at the end of the planning horizon. These two facts suggest that the fixed-price strategy and the 1.4 million cord constraint on aspen volume with the new set of yield reductions would be very difficult to achieve long term.

In terms of aspen volume produced, the amount of aspen volume harvested with the new set of parameters for the most optimistic and the most pessimistic scenarios is approximately the same as the baseline. However, the scenarios in between the most optimistic and more pessimistic one (future two to seven) produce less aspen volume due to the reduction of the yield multipliers.

On the test cases that used downward-sloping demand curves (Figure 4.8c and 4.8d), the amount of volume produced by all species as well as the aspen volume is very similar across both sets of multipliers. The shadow prices related to the aspen constraint are slightly higher with the new set of multipliers, but the difference is very small (around $5 or $7 in period 20). The increase in aspen shadow prices reflects the higher reductions in the aspen yield throughout the planning horizon. However, the flexibility that the downward-sloping demand curve gives to the model to find the equilibrium using the price/quantity relationship produces a lower impact of the new set of yield multipliers than the test case that uses a horizontal demand.
Figure 4.8 Volume of aspen harvested by period (two graphs on the left column) under (a) a horizontal demand curve and (b) the downward sloping demand curve 1 using the new set of yield multipliers. Aspen shadow prices ($/cord) associated with the aspen volume constraints (two graphs on the right column) under (c) a horizontal demand curve and (d) the downward sloping demand curve 1 (Legend: see numbering of the different scenarios in Figure 4.1)
4.4 Discussion

a) Impacts of using a specific demand curve on aspen volume

As explained in Chapter 3 the use of a horizontal demand curve for the aspen volume produces a highly unstable flow of timber throughout the planning horizon. Very high volumes are found at the beginning and the middle of the planning horizon, coinciding with the first and second rotation of aspen. These peaks also reveal the unbalanced age-class distribution of the aspen cover type at the beginning of the planning horizon. Without a reason for postponing the harvest for later periods, the model picks to harvest as much as it can in the first period, due to the financial maturity of much of the forest initially. Also, the use of a horizontal demand function does not penalize for harvesting more than the lower bound constraint on aspen volume, allowing the model to harvest large volumes in any period without a penalty. With the horizontal demand curve, shadow prices associated with the aspen volume constraints need to be very high at the end of the planning horizon to encourage and reward for postponing some volume of aspen to be harvested later, and therefore to be able to satisfy the minimum aspen constraint throughout the planning horizon. Those high prices associated with the aspen volume make this test case unsustainable long term from a realistic and practical perspective.

The use of a downward-sloping demand curve helps exactly add realism. With a downward-sloping demand function, periods with low volume are rewarded with a higher price, and periods with a high volume are penalized via a lower price. The steeper the demand curve, the greater the penalty or reward for a change in the quantity of timber provided. We can observe this exact behavior in our results. The downward trend found in the aspen volume reflects the core advantage of using this approach. The model finds the price/quantity equilibrium reducing the impacts of a forest age imbalance, regulating itself due to dropping the price in periods when harvest volumes are very high without the need of an even-flow constraint.
Regarding the all-specie flow, the use of a downward-sloping demand function on aspen does not modify completely the trend, but due to the change in the aspen flow, it certainly helps smooth the ups and downs that were found under the horizontal demand curve. The use of the demand curve 2 on the aspen volume does not dramatically change the results compared to the use of the demand curve 1. The flatter downward-sloping demand function, the lower the price given to a change in quantity, therefore the more similar it is to an unconstrained test case that uses a constant price (horizontal demand function). This fact is observed in the volume of aspen produced where we still see some large fluctuations in the quantity provided over time. The changes in aspen flow under the demand function 1 are smaller because the steeper the function adds more incentives to avoid abrupt fluctuations of the quantity over time.

b) Limit on Aspen Volume

Introducing the 1.8-million-cord upper bound on aspen has a different effect, depending on the demand curve used on the aspen volume. Under the horizontal-demand test case, shadow prices associated with the aspen volume constraints increase on the most pessimistic future (Future 4.8). When the 1.8 million-cord aspen limit is added the 1.4 million-cord lower bound constraint becomes harder to satisfy, needing to increase the shadow prices (reward) for that future to encourage postponing the harvest to later periods. As mentioned before, these high shadow prices suggest that this test case would be hard to maintain long term.

The use of a downward-sloping demand function seems to behave similarly with or without the upper limit on aspen volume.

c) Growth and Yield Multipliers: Sensitivity Analysis

Results are certainly sensitive to the assumptions on the parameters used. One of the parameters applied to the model is the set of yield multipliers used to define the impact
surrounding climate change on the growth and yield. The impact of the two different sets of parameters used in this study is clearer when using the horizontal demand function. In this case, the fixed-price demand and the lower bound constraint on aspen make the problem harder to solve with the more pessimistic set of multipliers. On the other hand, the sensitivity of the model about the yield multipliers seems to be less with a downward-sloping demand curve. This could be due to the fact that the two sets of parameters defined are similar to each other. To better understand the behavior of the model concerning the yield multipliers a deeper study on this topic would be needed.

4.5 Conclusions

The impact of climate change in forest ecosystems is a crucial and challenging topic for forest managers nowadays. The development and use of new approaches to adapt forest management decisions to a changing future is certainly a needed tool to add to our toolbox. In this application, a stochastic forest management model was successfully applied to a relatively big problem using a long planning horizon. We use and compare different demand curves to define the price/quantity relationship on aspen flow. The use of either demand function allows the option of adjusting harvest volume levels to make these levels price sensitive. A downward-sloping demand function gives the model the flexibility to obtain a more balanced and homogeneous trend in terms of volume and acres of aspen harvested as well as a lower future price. The biggest advantage of using the downward sloping demand curve is that the impacts of a forest age imbalance are reduced due to price incentives (and disincentives) to add stability to timber harvest volume flow levels over time.
BIBLIOGRAPHY

- Subalpine Fir Type in the Central and Southern Rocky Mountains. United States

possibility frontiers for wildlife habitat and timber value at the landscape level.

Algorithm for Stochastic Harvest Scheduling under Climate Change. in SSAFR,.

Available online at: https://doi.org/10.1007/BF01866919.

Scientific, Belmont, MA. 479–530 p.

Binder, S., R. G. Haight, S. Polasky, T. Warziniack, M. H. Mockrin, R. L. Deal, and G.
Arthaud. 2017. Assessment and Valuation of Forest Ecosystem Services: State of the
Agric. (May):NRS-170.

Science & Business Media.


Res. 31(1):99–110 Available online at:

Fire Effects Information System (FEIS). USDA For. Serv. Available online at:
https://www.feis-crs.org/feis/.


Minnesota Department of Natural Resources. DNR sustainable timber harvest analysis. 2018. Available online at: https://dnr.state.mn.us/forestry/harvest-analysis/index.html.


Available online at:


