The Effects of Climate Change on Tradeoffs in Forest Ecosystem Services

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Abstract

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Tradeoffs in Forest Ecosystem Services

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This sample dissertation is an aid to students who are attempting to format their theses with LaTeX, a sophisticated text formatter widely used by mathematicians and scientists everywhere.

- It describes the use of a specialized macro package developed specifically for thesis production at the University. The macros customize LaTeX for the correct thesis style, allowing the student to concentrate on the substance of his or her text.[1]

- It demonstrates the solutions to a variety of formatting challenges found in thesis production.

- It serves as a template for a real dissertation.

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[1] See Appendix A to obtain the source to this thesis and the class file.

TABLE OF CONTENTS

LIST OF FIGURES

GLOSSARY

CLIMATE SCENARIO: A projection of the future climate, specifically one used by the IPCC

ECOSYSTEM SERVICE: benefits that people receive from ecosystems, divided into four categories: supporting, provisioning, regulating and cultural [4]. Examples include food, soil formation, water purification, carbon storage, recreation, and education.

IPCC: the Intergovernmental Panel on Climate Change

CLUSTER: a set of contiguous forest stands

ACKNOWLEDGMENTS

I want to thank all those that contributed to my earning this degree.

DEDICATION

To ma femme and my family

Chapter 1

ASSESSING CHANGES IN TRADEOFFS AMONG ECOSYSTEM SERVICES IN THE DESCHUTES NATIONAL FOREST

1.1 Introduction

Forests play an important role in global ecological, social, and economic processes. They provide ecosystem services such as carbon storage, purification of water and air, wildlife habitat, recreation opportunities, and generate raw materials for goods such as food and lumber [13]. In managed forests, the extent to which forests provide these services depends on management practices. Optimal forest management seeks to ensure the sustained provision of these ecosystem services (!CITE bibtex'ed CFR source).

Like other ecosystems, forests will undergo changes as a result of the changing climate. Researchers anticipate new spatial distributions of tree species [25], increased sediment delivery to streams [22], and increasing disturbance regimes such as wildfires, drought, and insect infestation [45]. As this transformation occurs, forestsâĂŹ ability to provide ecosystem services will change. NEW GROWING CONDITIONS MAY LEAD TO INC/DEC TIMBER PRODUCTION. TEMPERATURES MAY POSITION FORESTS AS HABITAT FOR MORE/FEWER SPECIES. Increased frequency of wildfires will impact forestsâĂŹ ability to store carbon [6] and provide habitat for wildlife [32]. Water supplies that rely on forestsâĂŹ filtration capabilities may be impacted by the rising sediment levels predicted by [22].

Optimal forest management must consider the effects of the changing climate, because the time scale of forest development (decades) is the same as that on which climate change is predicted to operate (!CITE SOME REPORT that shows changes by late 21st century).

Hence, optimal forest management will likely differ between future climate scenarios !CITE climate change forest management papers. Decisions that would once have resulted in optimal achievement of ecosystem services, now under different climatic conditions, may no longer do so. Without consideration of climate change, forest management plans may restrict forests' potential to provide ecosystem services most effectively. To determine which management practices will be optimal in the future, we must first understand how climate change will impact forests' ability to provide ecosystem services. For example, how many tons of carbon dioxide will the forest be capable of storing? How many acres of forest will still qualify as suitable habitat for a particular species? Many studies have considered these questions !CITE SOME PEOPLE.

However, previous studies have addressed the impact of climate change on forest ecosystem services in isolation. Because forests provide these ecosystem services in concert with one another (see, for example, [43]), we must also understand how climate impacts the tradeoffs that exist among them. Consider the simultaneous provision of wildlife habitat, carbon storage, and resistance to wildfire. How does an increase in any one service alter our ability to acquire an amount of another? Relationships such as a marginal sacrifice in one service for substantial improvement in another may no longer exist under a new climate. To better ensure the sustained provision of ecosystem services, we must understand how these tradeoffs evolve as a function of climate.

Here, I use a watershed in the Deschutes National Forest as a case study to determine how climate change impacts optimal forest management and the changes in tradeoffs among ecosystem services.

TO TEST ALL THIS STUFF, I AM USING A STUDY AREA IN THE DESCHUTES NATIONAL FOREST, KNOWN AS THE DRINK AREA. IT IS THIS BIG AND IS DIVIDED INTO 303 FOREST STANDS. THE AREA CONTAINS THE WATERSHED FOR THE CITIES OF BEND AND SISTERS OREGON. IT IS COMPRISED OF OLD GROWTH AND NEW GROWTH AND SOME OTHER STUFF. IT IS FLAMMABLE. WE WANT TO REDUCE THE RISK OF LONGTERM, SEVERE DEGRADATION OF THE WATER

SUPPLIES TO THESE CITIES THAT WOULD RESULT FROM A HIGH SEVERITY WILDFIRE. THIS IS OUR FIRST OBJECTIVE. WE WILL DO THIS BY PERFORMING FUEL TREATMENTS. BUT THESE FUEL TREATMENTS LEAD TO SHORT-ERM SPIKES IN SEDIMENT CONTENT IN THE WATERSUPPLY, WHICH WE AIM TO MINIMIZE. MINIMIZING THE SEDIMENT DELIVERY TO THE WATERSHED AS A RESULT OF THE TREATMENTS IS OUR SECOND OBJECTIVE. FINALLY, THE AREA IS HOME TO THE FEDERALLY PROTECTED NORTHERN SPOTTED OWL. OUR THIRD OBJECTIVE IS ENSURING MAXIMAL HABITAT FOR THE NSO. WE WANT TO TEST OUR ABILITY TO SIMULTANEOUSLY PROCURE THESE THREE ECOSYSTEM SERVICES IN THE LONGTERM. BY LONGTERM, I MEAN I WILL STUDY IT OVER AN 80 YEAR HORIZON FROM 2015-2095. ALL MANAGEMENT ACTIVITY WILL OCCUR DURING THE INITIAL 40 YEARS. BC THE AREA GROWS SLOWLY, WE MODEL THESE 40 YEARS IN TWO 20-YEAR PLANNING HORIZONS. THE MANAGEMENT ACTIONS THAT MAY BE PRESCRIBED ARE THINNING TREATMENTS (SEE APPENDIX _ FOR TREATMENT PRESCRIPS) AND ARE DETERMINED APRIORI FOR EACH STAND AND TIME PERIOD COMBINATION. WE MEASURE THE SPIKE IN SEDIMENT DELIVERY AT THE TIME OF TREATMENT (YEARS 2025 AND 2045). WE MEASURE THE ACHIEVEMENT IN NSO HABITAT AND FIRE HAZARD AT THE END OF THE 80 YEAR PLANNING HORIZON. WE WILL DO THIS FOR EACH OF THREE DIFFERENT CLIMATE CHANGE SCENARIOS.

THE RESULTS WILL ENABLE US TO STUDY THE TRADEOFFS AMONG THESE THREE ECOSYSTEM SERVICES AND SEE HOW THEY VARY WITH CLIMATE CHANGE.

1.2 Methods

1.2.1 Simultaneous Provision of Ecosystem Services

Aiming to determine how climate change may destabilize the relationships between managed ecosystem services, I followed the IPCC's approach of using scenario-based analyses. I selected three climate projections for consideration. The first scenario is the assumption of no climate change. This is the default assumption for many current studies such as [37], from which this study is derived. I used this climate scenario as the control against which I compared the ecosystem service tradeoffs observed in the other scenarios.

The second and third scenarios are ensembles of climate models produced by research agencies recognized by the IPCC and assembled by the USFS [15]. Details about the global circulation models (GCMs) included in the ensembles can be found in [12]. The second scenario is an ensemble of models for Representative Concentration Pathway (RCP) 4.5 W/m^2, and the third scenario is the same ensemble of models for RCP 8.5 W/m^2. The RCPs indicate the additional radiative forcing (in W/m^2) above pre-industrial levels, with higher values of forcing indicative of more severe climate change. I chose these three scenarios because they represent a range of severity of climate change, from a $0°C$ warming by the year 2100 under the control (first scenario) to a $2.6 - 4.8°C$ warming under the third [24].

In order to provide a basis upon which to compare the tradeoffs among ecosystem services, I parameterized and solved a multi-objective mixed integer-linear mathematical program (MIP) for each climate scenario. The benefit of using this approach is that it produces a set of solutions indicating optimal simultaneous achievement in each of the considered ecosystem services. This set of solutions is known as an efficient frontier or a Pareto frontier. The solutions comprising the frontier are optimal, which means that - for ecosystem services which are in competition - an improvement in one ecosystem service cannot be achieved without sacrificing some amount of another. Prior to beginning this work, I determined that the objectives of reducing fire hazard, providing NSO habitat, and reducing sediment delivery were in conflict. Hence, the frontier generated by the multi-objective MIP provides a means to quantitatively study the conflict between these ecosystem services.

The Multi-objective MIP

The first objective is to minimize the average fuel model at the end of the 80-year planning horizon:

$$Minimize \quad \sum_{i \in I} \sum_{r \in R} F_{i,r} x_{i,r} \tag{1.1}$$

In equation (1.1), I sum over all stands $i \in I$ and all treatment prescriptions $r \in R$ to obtain a cumulative fire hazard metric. The coefficients $F_{i,r}$ are the area-weighted fuel models of each stand $i \in I$ at the end of the planning horizon if stand i is assigned to treatment prescription $r \in R$. The possible treatment prescriptions $r \in R$ are treat in the first period ($r = 1$), treat in the second period ($r = 2$), treat in both periods ($r = 3$), or do not treat ($r = 0$). I determined the type of treatment to be performed for a given stand in a given time period *a priori* depending on silvicultural characteristics, so the only decisions in the model are whether to treat a stand i according to treatment schedule r.

To determine the coefficients $F_{i,r}$, the fuel model for each stand under each treatment prescription, I began with the GNN structure map for map year 2012 (`http://lemma.forestry.oregonstate.edu/data/structure-maps`) from Oregon State University's Landscape Ecology, Modeling, Mapping & Analysis (LEMMA) group. I used this data with Climate FVS to project vegetation growth through the end of the 80 year planning horizon, using FVS's Fire and Fuels Extension (FFE) to obtain the average fuel model for each stand. I used a stand's area-weighted fuel model as a proxy for fire hazard, because the higher the fuel model, generally, the larger the fuel loading.

The second objective is to minimize the peak short-term sediment delivery that results from performing treatments in either period one (S_1) or period two (S_2):

$$Minimize \quad \max\{S_1, S_2\} \tag{1.2}$$

The last objective is to maximize the area of suitable northern spotted owl habitat at the end of the planning horizon.

$$Maximize \quad \sum_{i \in I_\omega} \left(a_i p_i + e a_i \left(\sum_{j \in R_i} x_{i,j} - p_i \right) \right) \tag{1.3}$$

The set of stands $i \in I_\omega$ are those that qualify as NSO habitat under at least one treatment prescription $j \in R_i$. If a stand i does not qualify as NSO habitat under any treatment prescriptions (if the set $R_i = \emptyset$), then $i \notin I_\omega$. If the model assigns a stand $i \in I_\omega$ a treatment prescription $j \in R_i$, then stand i qualifies as NSO habitat at the end of the planning horizon and it contributes to the objective function through a combination of its decision variable $x_{i,j}$ and its cluster inclusion trigger variable p_i. If the stand is part of a cluster of stands over 200 ha that all qualify as NSO habitat, then the variable $p_i = 1$, and it contributes an amount equal to the stand's area a_i. If stand i qualifies as NSO habitat, but it is not part of a 200 ha cluster of suitable habitat, then it contributes an amount equal to its area a_i discounted by a factor e. I define $e = 0.5$ in this model because of the sensitivity and large area requirements of the northern spotted owl [17].

A stand's qualifying for northern spotted owl habitat is dependent on three conditions: the presence of trees with DBH no less than 76 cm, average stand elevation less than 1830 m, and canopy cover of at least 60%. I used the same vegetation data to determine stands' NSO habitat suitability as that used to determine the fuel model coefficients $F_{i,r}$.

The objectives are subject to the following constraints. First, I define accounting variables for the sediment delivery that results from the performance of the prescribed management actions.

$$\sum_{i \in I} \sum_{r \in 1,3} s_{i,r} x_{i,r} = S_1 \tag{1.4}$$

$$\sum_{i \in I} \sum_{r \in 2,3} s_{i,r} x_{i,r} = S_2 \tag{1.5}$$

The coefficients $s_{i,r}$ are the amount of sediment (in tonnes) that would result from treating stand i according to prescription schedule r. To determine the sediment coefficients, I employed the online GIS-based Watershed Erosion Prediction Project (WEPP) tool [19]. To account for climate change, I used the climate data generated by Climate FVS to create custom climate files for the WEPP simulations.

In order to control the trigger variables p_i indicating a stand's inclusion in a 200 ha cluster of NSO habitat, I used the following two constraints:

$$\sum_{i \in D_c} \sum_{j \in R_i} x_{i,j} - |c| q_c \geq 0 \qquad \forall c \in C \tag{1.6}$$

$$\sum_{c \in C_i} q_c - p_i \geq 0 \qquad \forall i \in I_\omega \tag{1.7}$$

C is the set of all clusters whose combined area is greater than 200 ha. Equation (1.6) specifies that all stands $i \in D_c$ within a cluster $c \in C$ must be assigned a management prescription such that they meet all NSO habitat criteria in order for the cluster trigger variable q_c to take value 1.

Equation (1.7) specifies that if no cluster $c \in C_i$ - the set of clusters that contain site i - meets NSO qualifications, then the trigger variable p_i must equal 0. If some cluster $c \in C_i$ does meet NSO qualifications, then the objective function (1.3) will draw up the value of variable p_i to 1.

I also enforce the restriction that each stand may be assigned to at most one treatment prescription.

$$\sum_{r \in R} x_{i,r} = 1 \qquad \forall i \in I \tag{1.8}$$

Next, I ensured that the area treated in each time period is less than a prespecified maximum area A:

$$\sum_{i \in I} \sum_{r \in 1,3} a_i x_{i,r} = H_1 \tag{1.9}$$

$$\sum_{i \in I} \sum_{r \in 2,3} a_i x_{i,r} = H_2 \tag{1.10}$$

$$H_1 \leq A \tag{1.11}$$

$$H_2 \leq A \tag{1.12}$$

where the first two equations define the accounting variables for the areas treated in time periods 1 and 2, H_1 and H_2.

Finally, I specified fluctuation constraints to bound the differences in area treated in between time periods:

$$\ell H_1 - H_2 \leq 0 \tag{1.13}$$

$$-uH_1 + H_2 \leq 0 \tag{1.14}$$

I define a maximum of 20% fluctuation between time periods. That is, $\ell = 0.8$ and $u = 1.2$.

Together with the binary specifications on our variables in equation (1.15), the complete model is

$$Minimize$$

$$\sum_{i \in I, r \in R} F_{i,r} x_{i,r}$$

$$\max\{S_1, S_2\}$$

$$Maximize$$

$$\sum_{i \in I_\omega} \left(a_i p_i + e a_i \left(\sum_{j \in R_i} x_{i,j} - p_i \right) \right)$$

Subject to:

$$
\begin{aligned}
\sum_{i \in I} \sum_{r \in 1,3} s_{i,r} x_{i,r} &= S_1 \\
\sum_{i \in I} \sum_{r \in 2,3} s_{i,r} x_{i,r} &= S_2 \\
\sum_{i \in D_c} \sum_{j \in R_i} x_{i,j} - |c| q_c &\geq 0 \qquad \forall c \in C \\
\sum_{c \in C_i} q_c - p_i &\geq 0 \qquad \forall i \in I_\omega \\
\sum_{r \in R} x_{i,r} &= 1 \qquad \forall i \in I \\
\sum_{i \in I} \sum_{r \in 1,3} a_i x_{i,r} &= H_1 \\
\sum_{i \in I} \sum_{r \in 2,3} a_i x_{i,r} &= H_2 \\
H_1 &\leq A \\
H_2 &\leq A \\
\ell H_1 - H_2 &\leq 0 \\
-u H_1 + H_2 &\leq 0 \\
x_{i,r}, p_i, q_c \in \{0,1\} &\quad \forall i \in I, r \in R, c \in C
\end{aligned} \tag{1.15}
$$

1.2.2 Evaluating Climate Change Scenarios

Each point in the efficient frontier generated by the solution of the model described in §1.2.1 describes a prescription of management actions that, if followed, will produce an amount of NSO habitat, fire hazard, and sediment delivery as specified by the solution. The comparison of these frontiers allows

We drew on techniques used to compare sets of solutions in evolutionary algorithms.

Computing a Frontier's Solution Spacing

The spacing of solutions along the frontier provide a measure of flexibility for the decision maker. The more solutions

Computing a Frontier's Hypervolume Indicator

To compare the tradeoff structure of each climate change scenario's corresponding Pareto frontier, I calculated the relative volume of the objective space bound by the frontier. Computing such a volume for a two-dimensional frontier is trivial. Consider figure 1.1. The reader

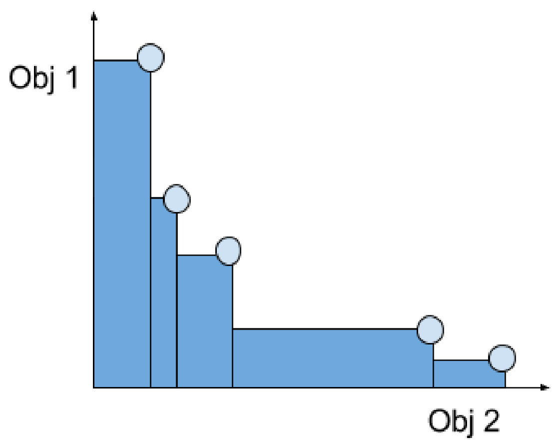

Figure 1.1: A two-dimensional frontier. The volume of this frontier may be computed by summing the areas of the rectangles shown.

can imagine a process to compute the volume whereby the frontier is divided into rectangles, as shown, and then summing the areas of these rectangles to get the total frontier volume.

Performing a similar computation in three and higher dimensions is less trivial and is an area of active research !CITESOMEONE. The higher-order volume computation is also often accomplished using Monte Carlo simulation !CITE SOMEONE.

I developed the following recursive algorithm to exactly compute the volume of an n-dimensional frontier for $n > 2$.

Given a set of Pareto optimal solutions $\mathcal{P}$ to a multi-objective mathematical programming model with a set of objectives O of cardinality $N := |O|$, this algorithm computes the volume V of the objective space bounded by the Pareto frontier defined by the solutions $x \in \mathcal{P}$. The objectives are assumed to be normalized so that the objective space is the N-dimensional unit hypercube with the origin and the point $\vec{\mathbf{1}}$ defining the nadir objective vector and the ideal objective vector, respectively. That is, all objectives are assumed to be maximized.

We project the objective space into $N-1$ dimensions by eliminating the dimension associated with an (arbitrarily-chosen) objective $p \in O$. We define the set of objectives $\overline{O} := O \backslash \{p\}$. It is assumed that $x \in \mathcal{P}$ are sorted in descending order according to p. The algorithm proceeds by sequentially adding solutions to the $(N-1)$-dimensional space, and calculating the contribution to the frontier volume as a product of the volume contribution in $N-1$ dimensions and its achievement in objective p.

Let $\overline{V_x}$ be the $(N-1)$-dimensional volume contribution of solution x and x_p be the achievement of solution x in objective p. Further, let F be the set of non-dominated solutions in $N-1$ dimensions. We proceed to compute the N-dimensional volume of the frontier V as follows.

The result of the algorithm is a single metric for each frontier, known as the hypervolume indicator !CITESOMEONE. This metric is used in the field of Evolutionary Algorithms for MultiObjOpt.

1.3 Results and Discussion

This sample thesis was produced by the LaTeX document class it describes and its format is consonant with the Graduate School's electronic dissertation guidelines, as of November, 2014, at least. However, use of this package does not guarantee acceptability of a particular thesis.

1.4 Conclusion

Here's a conclusion.

Figure 1.2: Algorithm to compute the volume of a Pareto frontier

$V \leftarrow 0$

$\overline{V} \leftarrow 0$

$F \leftarrow \emptyset$

for all $x \in \mathcal{P}$ **do**

  $\overline{V}_x \leftarrow \prod_{o \in \overline{O}} x_o - \overline{V}$

  for all $f \in F$ **do**

    if $f_o < x_o \forall o \in \overline{O}$ **then**

      $F \leftarrow F \backslash \{f\}$

    end if

  end for

  for all $o \in \overline{O}$ **do**

    $F_{x,o} := \{\, f \in F : f_o > x_o \,\}$

    Sort $f \in F_{x,o}$ in ascending order by their oth component, f_o

    $v_i \leftarrow x_o$

    for all $f \in F_{x,o}$ **do**

      $v_t \leftarrow f_o$

      $\delta_o := v_t - v_i$

      $\overline{V}_x \leftarrow \overline{V}_x + \delta_o \prod_{\sigma \in \overline{O} \backslash \{o\}} f_\sigma$

      $v_i \leftarrow v_t$

    end for

  end for

  $F \leftarrow F \cup \{x\}$

  $\overline{V} \leftarrow \overline{V} + \overline{V}_x$

  $V \leftarrow V + x_p \overline{V}_x$

end for

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Appendix A

WHERE TO FIND THE FILES

The uwthesis class file, `uwthesis.cls`, contains the parameter settings, macro definitions, and other TEXnical commands which allow LATEX to format a thesis. The source to the document you are reading, `kullman_thesis.tex`, contains many formatting examples which you may find useful. The bibliography database, `kullman_thesis.bib`, contains instructions to BibTeX to create and format the bibliography. You can find the latest of these files on:

- My page.

  `http://staff.washington.edu/fox/tex/uwthesis.html`

- CTAN

  `http://tug.ctan.org/tex-archive/macros/latex/contrib/uwthesis/`

  (not always as up-to-date as my site)