# The Effects of Climate Change on Tradeoffs in Forest Ecosystem Services

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## Abstract

The Effects of Climate Change on
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.


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

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# 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 [2]. Examples include food, soil formation, water purification, carbon storage, recreation, and education.

IPCC: the Intergovernmental Panel on Climate Change

# 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 [10]. 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 [19], increased sediment delivery to streams [17], and increasing disturbance regimes such as wildfires, drought, and insect infestation [39]. As this transformation occurs, forests 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 forests ability to store carbon [4] and provide habitat for wildlife [26]. Water supplies that rely on forests filtration capabilities may be impacted by the rising sediment levels predicted by [17].

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, [37]), 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.

## 1.2 Methods

### 1.2.1 Comparing climate change scenarios

### 1.2.2 Computing the volume of Pareto frontiers

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

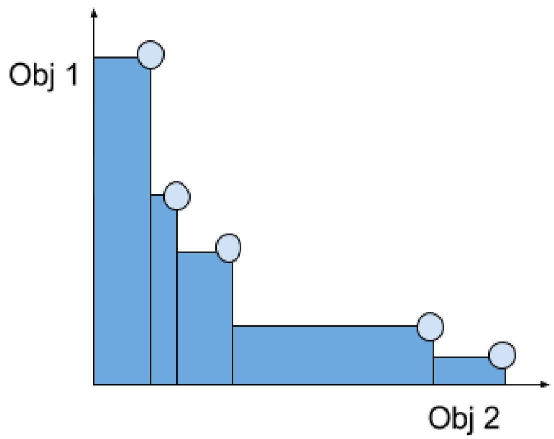


Figure 1.1: A two-dimensional frontier. The volume of this frontier may be computed by summing the areas of the rectangles shown.

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.

**Algorithm 1** Computing 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 $o$th 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)