Optimizing Forest Harvests & Grizzly Bear (*Ursus arctos horribilis*) Habitat

by

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Abstract

West-central, Alberta is subject to a growing number of resource extraction activities such as forestry that change ecosystem components and their structure. This area is important for the grizzly bear (*Ursus arctos horribilis*) population, which is considered to be a threatened species in Alberta because of low population densities, habitat fragmentation and increasing human-caused bear mortalities. Forest managers are under pressure to conduct sustainable forest management while protecting the grizzly bear population, which requires the understanding of the effects of forest harvesting on the grizzly bear habitat, including availability of food resources. The goal of this thesis is to find management strategies, that provide efficient combinations of timber value and grizzly bear habitat.

A linear programming technique was used to find harvest plans that maximize the production level of timber value subject to specified amounts of grizzly bear food items over a 200-year planning horizon. By finding harvesting plans for different amounts of grizzly bear food resources, a production possibility frontier was developed to examine trade-offs between timber management and occurrence of grizzly bear food resources that index habitat quality.

Forest harvesting did negatively effect the occurrence of some grizzly bear food items. However, the occurrence of some of grizzly bear food items, such as huckleberry and clover, declined if there is no harvesting. By maintaining 90% of the grizzly bear food items, maximum timber production could still be obtained. Although the results are specific to west-central Alberta and for grizzly bears, the approach used can be generalized providing the model and structure for future analyses.

Preface

This thesis is an original work by Pembegul Moradaoglu. No part of this thesis has been previously published.

In dedication to my parents *Nimet* and *Ali Pasa*.

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Chapter 1

Introduction

The brown bear (*Ursus arctos*) is one of the most widely distributed terrestrial mammals in the world and found from North America to the Middle East, even in North Africa (McLellan et al., 2008). The brown bear is in the species category of least concern in the International Union for Conservation of Nature (IUCN) red list of threatened species because of its extensive distribution (McLellan et al., 2008). Although it is still widely distributed, the brown bear range and population have nonetheless been declining and in some places becoming extirpated since the mid-1800s (Gailus, 2013). Human impact is the primary source of extirpation and habitat loss for large carnivores, such as bears (Woodroffe, 2000; Mattson and Merrill, 2002).

Grizzly bears (*Ursus arctos horribilis*), one of the subspecies of the brown bear, are found in the Arctic, western Canada and the north-western United States in North America (Alberta Grizzly Bear Recovery Plan 2008-2013, 2008). Western Canada is an important core area for the North American population (COSEWIC, 2012). While there is no clear evidence to prove the decline of the overall Canadian bear population, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) recently designated grizzly bears as a "*Species of Special Concern*" in Canada due to its sensitivity to expanding human activities (Parks Canada, 2014). Expanding human activities were the main reason for habitat loss and fragmentation of grizzly bear populations in Alberta and B.C. (Gailus, 2013). In Alberta, "grizzly bears occupy 35% (276,404 km^2/661,188 km^2) of the entire province" (Kansas, 2002) and the population has been estimated at around 700 bears in the provincial lands, in addition to small population in the national parks (Alberta Grizzly Bear Recovery Plan 2008-2013, 2008). Low population densities, slow reproductive rates, and increased human-caused bear mortalities generated conservation concern for grizzly bears. Due to the conservation concern, the government of Alberta listed grizzly bears as a *threatened species* in 2010 (ESRD, 2014b). Grizzly bears are considered as a flagship species for conservation in the northern Rocky Mountain Ecosystem (Gailus, 2013) and grizzly bears are local conservation issue in Alberta.

A steadily increasing human population increased resource extraction activities such as forestry, oil and gas in recent decades (Schneider et al., 2003; Nielsen et al., 2004a). Forests have become increasingly busy places because of resource extraction activities. In Alberta, the government regulates its policy of forest harvesting to support sustainable forestry (ESRD, 2014a). Forest managers are expected to develop a management plan that maintains biological diversity while achieving other goals, including timber production. Although numerous studies have been conducted on grizzly bear habitat, diet and conservation (Servheen, 1983; Banci et al., 1994; McLellan and Hovey, 1995, 2001; Apps et al., 2004; Nielsen et al., 2003, 2004a,b, 2010), there has not been any study undertaken to evaluate efficient combinations of grizzly bear food production and timber harvesting to inform forest management plans.

This thesis aims to inform management plans by examining the trade-off between forest harvesting and occurrence of grizzly bear food items in west-central Alberta. The study focused on the Yellowhead grizzly bear population unit. The area encompasses Whitehorse Wildland Provincial Park, Brazeau Canyon Wildland Provincial Park, and towns of Hinton, Robb and Cadomin (Figures 2.1 and 3.1). This thesis includes four chapters, including this introductory chapter and a concluding chapter. A brief description of each chapter is provided below following this general introduction.

In Chapter 2, I model the predicted probability of occurrence of grizzly bear food items for forested land covers and unforested land covers. More specifically, logistic regression models of grizzly bear food items for forested areas and unforested areas were estimated using the environmental characteristics (age, elevation, aspect and slope) of the study area. In Chapter 3, production trade-offs between timber harvesting and predicted probability of occurrence of grizzly bear food items are developed.

In the concluding chapter (Chapter 4), I present a general summary of the thesis.

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Chapter 2

Modelling distribution of grizzly bear food resources in west-central Alberta

2.1 Introduction

A forest ecosystem consists of biotic factors (plants, animals, micro-organism) and abiotic factors (non-living components). The maintenance and the sustainability of the forest ecosystem are important topics in forest biology and management; therefore, understanding the effects of different types of forest management regimes on species is critical (Kapos and Iremonger, 1998; Perry, 1998; Battles et al., 2001; Nielsen et al., 2004b). The grizzly bear (*Ursus arctos horribilis*), a large carnivorous mammal, is considered an indicator of a healthy ecosystem and a focal species for conservation in the Northern Rocky Mountains Ecosystem (Munro et al., 2006; Nielsen, 2011; Gailus, 2013). In recent decades, a steadily increasing human population and increased industrial resource extraction activities including agriculture, forestry and oil and gas have had substantial impacts on forests in Western Canada (Banci et al., 1994; Schneider et al., 2003; Nielsen et al., 2004a). These industrial activities have changed ecosystem components and their structure; for example, unforested areas have expanded and forest land has become more fragmented and younger (Schneider et al., 2003). Furthermore, the changed landscape structure and composition affect the distribution of grizzly bears (Reed et al., 1996; Popplewell et al., 2003). Grizzly bear populations are fragmented into small sizes and homogenized because of isolation from larger population (Carroll et al., 2001). These fragmentation and homogenization result in low genetic variability which, makes it difficult for population to adapt to environmental changes and, therefore, threatens grizzly bear populations with extirpation. Small population size, slow reproductive rate and population decline creates concern for grizzly bear persistence in west-central Alberta (Alberta Grizzly Bear Recovery Plan 2008-2013, 2008). Moreover, grizzly bears have been considered as a *threatened species* in Alberta since 2010 by Government of Alberta (ESRD, 2014).

An combination of treed and non-treed land provides optimal grizzly bear habitat (Herrero, 1972; Mealey, 1980; Servheen, 1983). Recent studies have mentioned the different habitats selected by grizzly bears. Studies done by McLellan and Hovey (2001) and May et al. (2008) indicate that grizzly bears select treed habitats. However, Nielsen et al. (2004a) argues that clearcuts have been chosen by grizzly bears in a different manner depending on the seasons and silvicultural histories of land. More specifically, grizzly bears were attracted by clearcut habitat because of a lack of natural openings in the area, and the occurrence of important nutrition resources for grizzly bears in the clearcuts. Other studies show bare rock, burned forest habitat and road-like habitats have also been selected by grizzly bears (Apps et al., 2004; Roever et al., 2008).

Habitat selection by grizzly bear varies for different reasons, such as seasons, as grizzly bears have three forage seasons, (Servheen, 1983; Nielsen et al., 2004a), and demographic features of sex or age (Mace et al., 1999; Roever et al., 2008). Although studies show various reasons for grizzly bears habitat selection, they all share common denominators, of food resource availability and nutrition/energy ratio (McLellan and Hovey, 1995; Nielsen et al., 2003; Munro et al., 2006). Distribution of food items depends on environmental factors, such as land cover, age and elevation. Here we analyze the presence and absence of grizzly bear food resources (GBFR) in order to determine forest management and conservation and maintenance of grizzly bear population. The intent is to produce a predictive model of GBFR for incorporation into forest management planning models which will be examined and explained in the next chapter. More specifically, we explore how age, land cover, age-land cover interaction, elevation, aspect and slope affect the distribution of 21 grizzly bear food items. The objectives of this study are as follows: (1) develop models to describe GBFR occurrence within our study area, (2) group grizzly bear foods to determine the best food resource areas. Determining the distribution of food resources will aid us in managing bears in the study area.

2.2 Materials and methods

2.2.1 Study area

The study area is approximately 535,000 ha located in Yellowhead grizzly bear population unit in west-central Alberta (centered on $53^\circ\ 6'$ N $117^\circ\ 1'$ W; Figure 2.1). The area encompasses Whitehorse Wildland Provincial Park, Brazeau Canyon Wildland Provincial Park, and the towns of Hinton, Robb and Cadomin. Provincial parks cover 19,000 ha, which is 3.7% of the study area. Elevation varies from 946 to 2887 m. The land cover is dominated by conifer forests. A small portion of the land is covered with mixed and broadleaf forest, regenerating forest, wetland and rocks. The forest age in the study area ranges from 6 to 425 years old.

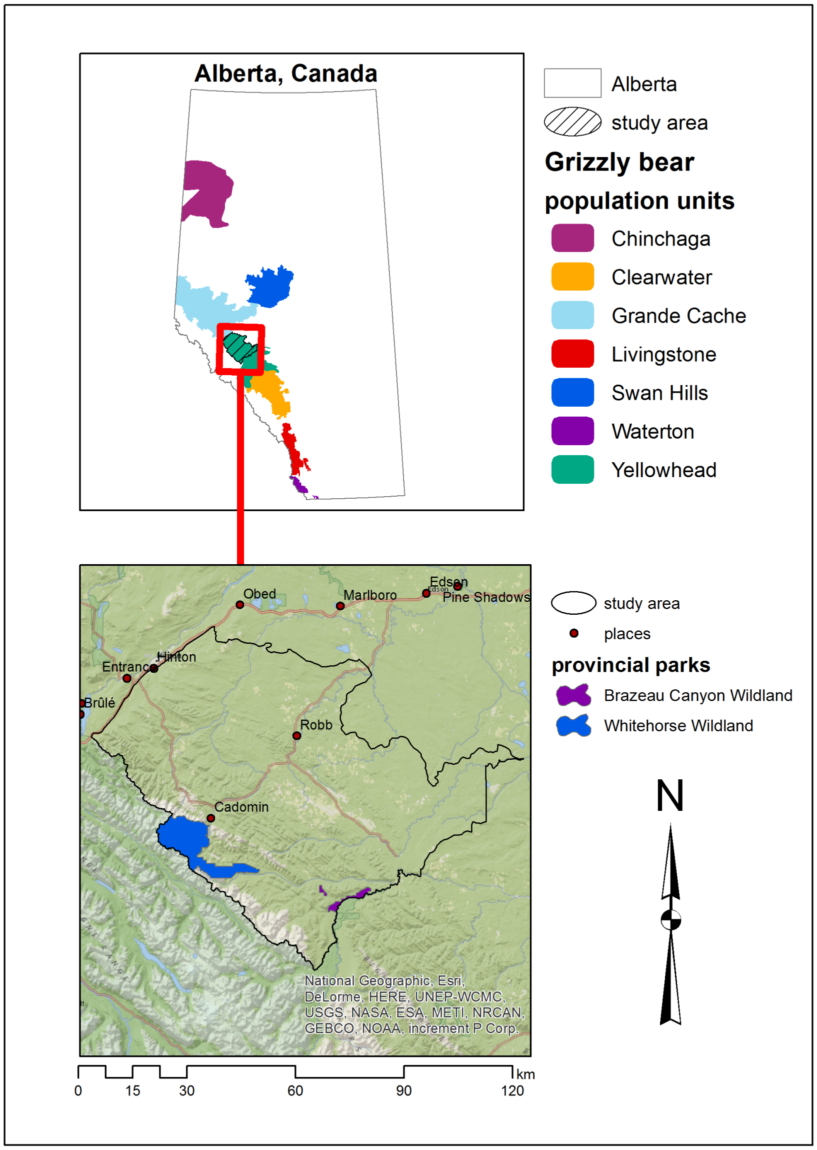

Figure 2.1: Map of the study area in west-central Alberta, showing towns, study area boundary and grizzly bear population units of Alberta, Canada

2.2.2 Model variables

Statistical analysis and other calculations were done in R (R Code Team, 2013) to model the distribution of GBFR .

Grizzly bear food data

Knowledge of grizzly bear diet was obtained by Munro et al. (2006). There were 1650 random sample plots (20×20 m) visited by Nielsen et al. (2010). At each field plot, 20-m transects were established for identification of whether GBFR are present (1) or absent (0) within the plots. 1532 sample plots were inside the study area boundary. Details of how the field study was done can be found in Nielsen et al. (2004b). The grizzly bear foods and their abbreviations are described in Table 2.1.

The grizzly bear foods were divided and coded in four groups in order to estimate the study area weighted probability of food distribution: (1) Green vegetation, (2) Fruit, (3) Root and (4) Animal matter (Table 2.2).

Table 2.1: List of grizzly bear food items captured in sample plots by (Nielsen et al., 2010) and their abbreviation (code).

Grizzly bear food	Abbreviation
Equisetum spp. (horsetail)	equisetum
Heracleum lanatum (cow-parsnip)	hela
Taraxacum officinale (dandelion)	taof
Trifolium spp. (clover)	clover
Amelanchier alnifolia (saskatoon)	amal
Arctostaphylos uva-ursi (bearberry)	aruv
Empetrum nigrum (crowberry)	emni
Fragaria virginiana (strawberry)	frvi
Ribes spp. (currants)	ribes
Rubus idaeus (raspberry)	ruid
Shepherdia canadensis (buffaloberry)	shca
Vaccinium membraneceum (huckleberry)	vame
Vaccinium myrtillus (blueberry)	vamy
Vaccinium scoparium (grouseberry)	vasc
Vaccinium vitis (cowberry)	vavi
Vibirnum edule (highbush cranberry)	vied
Hedysarum alpinum (sweet vetch)	heal
Hedysarum alpinum (sweet vetch)	hedy
Ants (*Hymenoptera* insects-mostly ants)	anting
Ungulate carcass (mostly moose)	ungulate_k
Wasp (*Hymenoptera* insect-except ants)	wasp

Table 2.2: Description of grizzly bear food resource groups.

Groups name	Code	Individual Food Items Name
Green vegetation	1	*Equisetum* spp. (horsetail) *Heracleum lanatum* (cow-parsnip) *Taraxacum officinale* (dandelion) *Trifolium* spp. (clover)
Fruit	2	*Amelanchier alnifolia* (saskatoon) *Arctostaphylos uva-ursi* (bearberry) *Empetrum nigrum* (crowberry) *Fragaria virginiana* (strawberry) *Ribes* spp. (currants) *Rubus idaeus* (raspberry) *Shepherdia canadensis* (buffaloberry) *Vaccinium membraneceum* (huckleberry) *Vaccinium myrtillus* (blueberry) *Vaccinium scoparium* (grouseberry) *Vaccinium vitis* (cowberry) *Vibirnum edule* (highbush cranberry)
Root	3	*Hedysarum alpinum* (sweet vetch)
Animal matter	4	Ants (*Hymenoptera* insects-mostly ants) Ungulate carcass (mostly moose) Wasp (*Hymenoptera* insect-except ants)

Environmental variables considered

Environmental variables of the study area were age, land cover, elevation, aspect and slope. Land cover, elevation, aspect and slope variables were obtained for each 30 m × 30 m pixel of the study area, age variable was obtained for most part of the study area for each 30 m × 30 m pixel.

The entire study area was represented by 14 land cover classes (McDermid et al., 2009) (Table 2.3), derived from remote sensing imagery (Landsat) for each 30 m × 30 m pixel. For the statistical procedure, the land cover classes were coded as dummy variables to determine whether land cover type has an effect on distribution of GBFR. For example, if the dummy variables set to be occurrence of dense conifer forest for each 30 m × 30 m pixel, it was codded as (1) presence, otherwise (0) absence.

Table 2.3: Names of land cover types, land cover abbreviations, their proportion in the study area and dummy variable abbreviations. LC1 to LC6 represent forested habitat, and LC7 to LC16 represent unforested habitat.

Land cover name	Abbreviations	Area (ha)	Percent (%)	Dummy code
Dense conifer forest	DC	139,103	26.0	LC1
Moderate conifer forest	MC	163,140	30.5	LC2
Open conifer forest	OC	11,162	2.1	LC3
Mixed forest	MF	62,964	11.8	LC4
Broadleaf forest	BF	14,380	2.7	LC5
Treed wetland	TW	19,384	3.6	LC6
Open wetland	OW	4,013	0.7	LC7
Shrubs	Sh	44,233	8.3	LC8
Herbaceous	Herb	26,683	5.0	LC9
Barren Land	BL	45,177	8.4	LC12
Water	Wtr	1,302	0.2	LC13
Snow/Ice	S/I	38	0.0	LC14
Cloud/No Data	Cld	10	0.0	LC15
Shadow/No Data	Shdw	3,502	0.70	LC16

Age variable consists of forested area age and unforested area age. Unforested area, representing a combination of cutblocks, rocks, water, ice, snow or no data resulting from cloud or shadow, age was given a zero (0). Forest origin data, derived from the Alberta Vegetation Inventory (AVI) for each 30×30 m pixels of the study area, was subtracted from 2007 to calculate forested area age. The reason why 2007 was used for subtraction is because forest origin data was provided in the year 2007. Forest age varied from 20 to 400 years. However, the majority of the forests were between 100 and 120 years old (Figure 2.2).

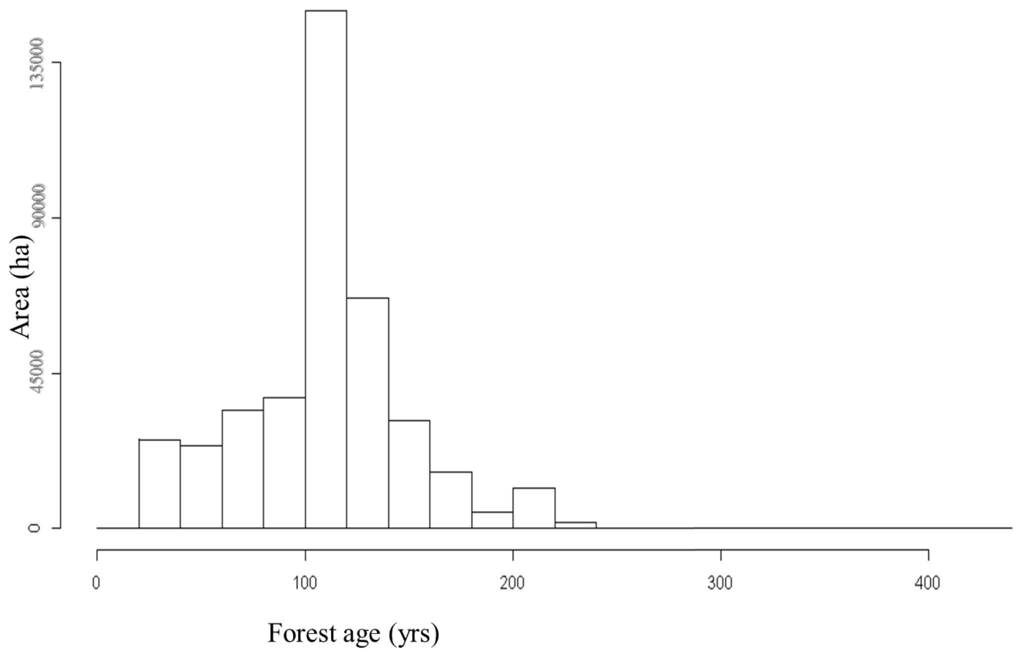

Figure 2.2: Age class distribution of forested land cover in the study area. Forest age varies between 20 to 400

Land cover and forest origin data were provided by Foothills Research Institute Grizzly Bear Program.

Elevation, aspect and slope were used to characterize the topographic condition of the study area. Elevation variable was derived from approximately 90 meter digital elevation model (DEM) (CGIAR-CSI, 2004). From this DEM, aspect and slope were calculated and measured in degrees in R programming language with function `terrain` in raster packages (Hijmans et al., 2014). Then the aspect unit was converted to cosines (equation 2.1). The reason was to reflect aspect's effect properly into the models. Aspect ranged from 0° to 360°; for example, the north aspect was identified with 1° and also 359°, which cannot be interpreted correctly for model evaluation by the programming. Aspect ranged from 1 to -1, north to south or vice-versa, respectively, with cosine conversion.

$$\text{aspect\_cos} = \cos(\text{aspect}^\circ * \left(\frac{\pi}{180}\right) \tag{2.1}$$

Quadratic terms were created to allow for non-linear responses of GBFR to some environmental variables. The agesquare represents the square of age and the elevsquare represents the square of elevation. Agesquare and elevsquare were the quadratic terms of this study to allow non-linear responses of species to these factors.

Interaction variables were used to understand the interaction of forest cover type and age on presence/absence of GBFR. They were obtained from multiplying land cover dummy variables by age. Interaction variables (land cover-age interaction) were only calculated for forested land cover types. It is important to understand this combination effect on GBFR to manage the forest while protecting GBFR.

2.2.3 Model development

Logistic regression models were estimated in R (R Code Team, 2013) to evaluate the probability of GBFR occurrence in the study area. The dependent variable is categorical and the independent variable is either categorical or continuous in the logistic regression model (Anderson, 1982). The main reason to use logistic regression for modelling was because dependent variables were categorical and independent variables were either categorical or continuous in this study.

Variable selection is the critical process for the model estimation. The traditional approach of selection is to minimize the number of variables included in the model until finding the most parsimonious model that still explains the data (Hosmer and Lemeshow, 2000; Bursac et al., 2008). However, some methodologists suggest inclusion of all variables in the model without looking at their significance level. This approach could result in numerically unstable estimates (Hosmer and Lemeshow, 2000). In this study, I have decided that land cover variables are critical for predicting occurrence of grizzly bear food resources. I will keep land covers variables in the model, other variables selected with variable selection method suggested by Hosmer and Lemeshow (2000) to find the most parsimonious models which predict the occurrence of GBFR.

The variable selection approach can be divided into four steps. It starts with univariate analyses of each variable one at a time. Variables are eliminated in the first step if their significance level is larger than the significance level (α) selected by analyst. In the second step, an iterative process of multivariate analysis is performed. Multivariate analysis starts with the "*intercept only*" model, then variables will be added in the model one at a time according to their significant level, starting from the most significant variable. At the end of the multivariate analysis (step 3), variables, which are eliminated in the univariate analyses, will be added back to see if they have a significant effect on the model with the association of other variables even they were insignificant by themselves for the dependent variable. In the fourth step, interaction variables will be added to check whether they should be included in the model. The end result of this process is a predictive model with important independent variables. Details of this approach can be found in Hosmer and Lemeshow (2000).

The occurrence of GBFR data was obtained from 20 m $\times$ 20 m random sample plots and recorded as a point data with its center point coordinates; however, independent variables of the models were obtained from 30 m $\times$ 30 m pixels raster data. These different sized and type data sets were intersect each other in R programming language with function `extract` (Hijmans et al., 2014). This function returned the values of pixels in which a set of sample plot points fall. That is why the probability of finding GBFR was predicted from the random sample plots for pixels.

Modelling the occurrence of grizzly bear individual food items

GBFR data obtained from randomly selected 1532 sample plots were modeled as a function of land cover dummy variables, age, elevation, slope, aspect_cos, agesquare (age square), elevsquare (elevation square) and interaction variables. For each grizzly bear individual food resources, two models were developed to understand forested and unforested land cover effect on the occurrence of GBFR. Age, agesquare and interaction variables were included in the analyses where forested land covers were used.

Alpha levels 0.15 and 0.20 were selected for the univariate and multivariate analyses elimination criteria, respectively, as suggested by Hosmer and Lemeshow (2000). The *Intercept only* model included land cover dummy variables and they were kept in the model without looking at the significance level because of their critical effects on predicting occurrence of GBFR.

Logistic regression models were developed in R (R Code Team, 2013) with function `glm` for forested and unforested land cover for each of the 21 individual grizzly bear food resources. Below are the examples of models for clover, one of the food items (Equations 2.2 and 2.3), where IV3 and IV5 stand for interaction variables and LC1 to LC12 stand for land cover dummy variables. Description of model variables is in Table 2.4.

$$\begin{aligned}\texttt{model1} =& \texttt{glm(clover} \sim \texttt{LC1} + \texttt{LC3} + \texttt{LC4} + \texttt{LC5} + \texttt{LC6} + \texttt{age} + \texttt{elevsquare} \\ &+ \texttt{elevation} + \texttt{aspect\_cos} + \texttt{IV3} + \texttt{IV5})\end{aligned} \tag{2.2}$$

$$\begin{aligned}\texttt{model2} =& \texttt{glm(clover} \sim \texttt{LC7} + \texttt{LC9} + \texttt{LC12} + \texttt{elevsquare} + \texttt{elevation} \\ &+ \texttt{aspect\_cos})\end{aligned} \tag{2.3}$$

Moderate conifer forest type (LC2), moderate conifer-age interaction (IV2) and shrubs (LC8) were not included in the models. They were chosen as reference variables, because moderate conifer forests (LC2) were the most common cover type between the forested land cover, and also shrubs (LC8) were the most common cover type between the unforested land cover types. There was no recorded data for water (LC13), snow/ice (LC14), cloud (LC15) and shadow (LC16) in the sample transects and thus they were not included in the model. Other variables were not in the model because their significance levels were greater than 0.20.

After selecting the final model for each food items, the function `predict` in R (R Code Team, 2013) was used for two models to get a predicted probability of occurrence of GBFR for the study area with the pixel-based environmental data. The two models' results were combined according to their land cover type for each pixels to create a predicted probability of occurrence of GBFR for the study area. For example, if the land cover type was conifer forest for pixel, equation 2.2 was chosen to predict the occurrence of clover.

Table 2.4: Description of environmental variables used to model predicted probability of occurrence of grizzly bear food items in the study area.

	Variable name	Variable code	Units and range
Forested land cover dummy variables	Dense conifer forest	LC1	Categorical - 0 or 1
	Moderate conifer forest	LC2	Categorical - 0 or 1
	Open conifer forest	LC3	Categorical - 0 or 1
	Mixed forest	LC4	Categorical - 0 or 1
	Broadleaf forest	LC5	Categorical - 0 or 1
	Treed wetland	LC6	Categorical - 0 or 1
Unforested land cover dummy variables	Open wetland	LC7	Categorical - 0 or 1
	Shrubs	LC8	Categorical - 0 or 1
	Herbaceous	LC9	Categorical - 0 or 1
	Barren Land	LC12	Categorical - 0 or 1
Stand condition	Age	age	Years - 0 to 425
	Age^2	agesquare	years^2 - 0 to 180,625
Terrain condition	Elevation	elevation	meter - 946 to 2887
	Elevation^2	elevsquare	m^2 - 894,977 to 8,335,497
	Slope	slope	degree - 0 to 75
	Aspect	aspect_cos	Unitless - (-1) to (1)
Interaction dummy variables	Dense conifer & Age	IV1	Years - 0 to 425
	Moderate conifer & Age	IV2	Years - 0 to 425
	Open conifer & Age	IV3	Years - 0 to 327
	Mixed & Age	IV4	Years - 0 to 425
	Broadleaf & Age	IV5	Years - 0 to 411
	Treed wetland & Age	IV6	Years - 0 to 227

Weighted probability of occurrence of grizzly bear grouped food items

Individual grizzly bear food resources were grouped by foraging type in order to evaluate each pixel's importance of the weighted food group predicted probability of occurrence. Importance of grizzly bear foods differ depending on the percent volume of the food items in the fecal of grizzly bears. Eight (8) GBFR percent volume in the fecal were reported in different time periods of the year by Munro et al. (2006). I used these data to calculate importance weight (index) of each food item within the particular food group to which each belonged following approaches similar to that of Nielsen et al. (2010).

There were three steps for calculating the weight (index) of individual food resources. In the first step, percent volume of each food item in ten (10) time periods were summed up individually. In the second step, summed percent volume of individual food items added together according to the group they were in. In the final step, the summed percent volume of individual food item was divided by summed percent volume of grouped data which belonged.

The predicted probability of individual food items were multiplied by their index (Table 2.5). They were then added together according to which group they belong to find out weighted food group predicted probability. Eight (8) of the GBFR had index data. Thus, the food items which had the index data were just used to discover the occurrence of grizzly bear grouped food items.

Table 2.5: Grizzly bear individual food items index and their group.

Group name	Food item name	Food item code	Index
Green vegetation	*Equisetum* spp. (horsetail)	equisetum (1)	0.35
	Heraculum lanatum (cow-parsnip)	hela (2)	0.50
	Trifolium spp. (clover)	clover (3)	0.15
	Total		1.00
Fruit	*Shepherdia canadensis* (buffaloberry)	shca (4)	0.71
	Vaccinium membraneceum (huckleberry)	vame (5)	0.29
	Total		1.00
Root	*Hedysarum alpinum* (sweet vetch)	hedy (6)	1.00
	Total		1.00
Animal matter	Ants (*Hymenoptera* insects-mostly ants)	anting (7)	0.10
	Ungulate carcass (mostly moose)	ungulate_k (8)	0.90
	Total		1.00

2.3 Results and discussion

2.3.1 Distribution of individual food items

Environmental variables, which include land cover, age, agesquare, elevation, elevsquare, aspect, slope and land cover-age interaction, affected the occurrence of GBFR either positively or negatively according to logistic regression results. The effect of land cover types, age and elevation were more obvious and predominant on almost all GBFR. Tables 2.6 and 2.7 show result of logistic regression models and variables coefficient (see appendix A for detailed example and explanation of the magnitudes of coefficients).

The occurrence of saskatoon had no correlation with either forested land cover types or unforested land cover types. It had high probability to occur in areas of high slope inside unforested habitat. Clover and dandelion had high probability to be in the young broadleaf forest at high elevation; however, they had low probabilities of occurrence in the dense conifer forest. Moreover, both had high probability to occur in the herbaceous land at high elevations. On the other hand, clover was negatively associated with broadleaf-age interaction and positively associated with open conifer-age interaction.

The occurrence of cow-parsnip and horsetail had no association with forested land cover types, but they were positively or negatively associated with unforested land cover types. Moreover, they had different responses to environmental variables (Nielsen et al., 2010). More specifically, cow-parsnip has significant positive relation with dense conifer and age interaction; saskatoon and horsetail had positive correlation with broadleaf and age interaction.

Ants were predicted to be in the mixed forest at high probability and they had negative correlation with dense conifer forest habitat. Also, ants were negatively correlated with unforested cover types. Previous work has shown age and occurrence of ants are negatively correlated (Nielsen et al., 2010); however, our study showed that age or age-land cover interaction variables had an effect on the occurrence of ants. The reason could be the environmental variables used to predict the occurrence of ants were differ in these two studies. Also, study area boundaries were different in these two studies. For example, our study area does not include Jasper National Park.

In forested land cover, moose had high chance to occur in the treed wetland forest at high elevations but low chance to occur in the moderate conifer forest. As discussed by Maier et al. (2005), the moose population prefers to be in the riparian habitat. Furthermore, moose habitat had a positive relation with mixed forest-age interaction variables, which means they inhabit in the mature mixed forest as well. In unforested land scape, they had positive correlation with elevation, but a negative correlation with shrub land cover. Insects (except ants) had no significant relation with any of the environmental variables in the forested habitat; however, it had high probability to be at low elevation and high slope in the unforested habitat.

The occurrence of sweet vetch was negatively correlated with the elevation factor while positively correlated with the elevsquare factor, which means moose had a non-linear relation with elevation. Sweet vetch was predicted to be in the mountain environment at high probability; thus, bears would have high root matter in their diet (Munro et al., 2006). It had a positive association with dense conifer - age interaction, while it was negatively correlated with age and dense conifer land cover by itself. On the other hand, sweet vetch had high probability to be in the shrub land and low probability to be in the barren land in unforested habitat.

Bearberries had higher probabilities than other GBFR that were predicted to be in the old open conifer forest at low elevation, high slope and no aspect. While bearberries were positively associated with age and agesquare, they had negative association with dense conifer land cover - age interaction. So bearberries do not always occur in old forests. Strawberry, currants, huckleberry, grouseberry and crowberry had no significant relation with either land cover types or interaction variables in forested area; also they did not have significant relation with land cover types in the unforested area except for crowberry. Crowberries had high chance to be in open wetland at high elevations. Strawberries had high probability of occurrence at low elevations with no aspect; however, currants had low probability of occurrence at high elevations with sunny aspect.

Buffaloberry and cowberry had high chance to be in the mature dense conifer and mixed forests. A previous study done by Nielsen et al. (2010) predicts that buffaloberry occurs in the forested area at low elevations, which supports the result of our study for buffaloberry. On the other hand, cowberries had higher probability to occur in the high elevation areas. Similar to prior work Nielsen et al. (2010), raspberries had low chance to be in mature dense conifer forests unlike buffaloberries and cowberries. Raspberries appeared to be in younger broadleaf forests at high slope and high elevation. Roberts et al. (2014) also showed that occurrences of raspberries increase at higher elevation. Buffaloberry and cowberry were negatively related with unforested land cover types while raspberries had no significance relation with unforested cover types. Buffaloberries and cowberries had a positive relation with age variable unlike raspberries; however, raspberries had a positive relation with land cover-age interaction while buffaloberries and cowberries were negatively correlated.

Blueberry and highbush cranberry had higher probability to occur in the old mixed forest, as indicated in a previous study done by Noyce and Coy (1990) that relates mature forest and occurrence of blueberry, and also they had a quadratic relation with age variable. Highbush cranberries were predicted to be in broadleaf forests at high elevation, high slope and aspect . Also, blueberries were positively correlated with broadleaf forest-age interaction.

Land cover and age interaction variables mostly had different effect on the occurrence of GBFR than when land covers and age were involved the models individually. Clover and sweet vetch were two examples to see this difference. Interaction variables changed both the direction of the relation and the related variables; for example, blueberries had positive significance relation with mixed forest (LC4) while mixed forest - age interaction variable had no relation with blueberries.

Table 2.6: Model coefficients for grizzly bear food resources in forested habitat (See Tables 2.1 and 2.4 for abbrevations), the numbers inside the table are in scientific notation form.

Variables	Grizzly bear food items					
	saskatoon	clover	horsetail	cow-parsnip	dandelion	anting
Dense conifer	-1.588×10^{1}	-7.472×10^{-1}*	-5.287×10^{-1}	-8.265×10^{-1}	-1.198*	-7.610×10^{-1}*
Open conifer	-1.592×10^{1}	-1.331	2.334×10^{-1}	-7.237×10^{-1}	-3.713×10^{-1}	4.673×10^{-1}
Mixed forest	1.005	-2.474×10^{-1}	-8.529×10^{-2}	5.740×10^{-1}	-1.763×10^{-1}	5.233×10^{-1}*
Broadleaf forest	4.565×10^{-1}	1.967*	3.666×10^{-1}	8.621×10^{-1}	1.090*	3.921×10^{-1}
Treed wetland	-1.589×10^{1}	-2.780×10^{-1}	-1.162	-1.253×10^{1}	-1.409	2.229×10^{-1}
age		-1.050×10^{-2}*			-1.036×10^{-2}*	
agesquare						
elevation	8.035×10^{-2}	1.261×10^{-2}*		2.405×10^{-2}*	1.039×10^{-2}*	
elevsquare	3.362×10^{-5}	-4.840×10^{-6}*	-1.461×10^{-7}	-6.888×10^{-6}*	-4.270×10^{-6}*	-4.869×10^{-7}*
slope	1.385×10^{-1}		-5.624×10^{-2}*			3.335×10^{-2}
aspect_cos	-9.949×10^{-1}	-1.377×10^{-1}	1.139×10^{-1}		-1.475×10^{-1}	-2.174×10^{-1}*
Dense conifer&age			4.174×10^{-3}	1.172×10^{-2}*		
Open conifer&age		1.923×10^{-2}*				
Mixed forest&age					-6.646×10^{-3}	
Broadleaf forest&age	2.489×10^{-2}	-6.482×10^{-2}*	-1.821×10^{-2}		-2.019×10^{-2}	
Treed wetland&age			1.567×10^{-2}			
Constant	-5.348×10^{1}	-8.636*	3.708×10^{-1}*	-2.311×10^{1}*	-6.502*	-1.187*
AUC	0.912	0.720	0.636	0.711	0.756	0.651

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Table 2.6 – continued from previous page

Variables	Grizzly bear food items					
	ungulate_c	other insects	sweet vetch	sweet vetch_2	bearberry	strawberry
Dense conifer	9.942×10^{-1}	1.252	–1.463	–1.634*	5.259×10^{-1}	-2.625×10^{-1}
Open conifer	3.151×10^{-1}	-1.351×10^{1}	-5.464×10^{-1}	-9.242×10^{-1}	9.184×10^{-1}*	3.997×10^{-1}
Mixed forest	–2.335	1.176	1.738×10^{-2}	-6.667×10^{-2}	2.115×10^{-2}	2.213×10^{-1}
Broadleaf forest	-1.403×10^{1}	1.160	5.723×10^{-1}	2.175×10^{-1}	-6.215×10^{-1}	-4.655×10^{-1}
Treed wetland	2.994*	-1.444×10^{1}	-1.310×10^{1}	-1.435×10^{1}	1.240	-6.845×10^{-1}
age		5.952×10^{-3}		-3.915×10^{-3}	-3.328×10^{-3}*	1.564×10^{-2}*
agesquare				-1.146×10^{-4}*		
elevation	2.326×10^{-2}*	-3.718×10^{-2}	-1.001×10^{-2}*	-1.448×10^{-2}*	-1.505×10^{-2}*	-6.365×10^{-3}*
elevsquare	-7.124×10^{-6}*	8.911×10^{-6}	4.279×10^{-6}*	5.538×10^{-6}*	4.499×10^{-6}*	1.244×10^{-6}
slope		3.072×10^{-1}			4.580×10^{-2}*	2.311×10^{-2}
aspect_cos		1.292			-7.153×10^{-1}*	-3.853×10^{-1}*
Dense conifer&age	-8.350×10^{-3}		9.900×10^{-3}	1.070×10^{-2}*	-1.206×10^{-2}*	
Open conifer&age				1.064×10^{-2}		
Mixed forest&age	2.690×10^{-2}*					4.602×10^{-3}
Broadleaf forest&age						1.844×10^{-2}
Treed wetland&age					-5.880×10^{-2}	
Constant	-2.282×10^{1}*	2.303×10^{1}	2.613	7.313*	9.656*	5.913*
AUC	0.751	0.910	0.827	0.786	0.729	0.714

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Table 2.6 – continued from previous page

Variables	Grizzly bear food items					
	currants	raspberry	buffaloberry	huckleberry	blueberry	grouseberry
Dense conifer	-9.903×10^{-2}	-1.529*	9.910×10^{-1}*	2.596×10^{-1}	4.266×10^{-1}	-1.800×10^{-1}
Open conifer	-3.096×10^{-1}	-2.097×10^{-1}	-1.249	3.407×10^{-1}	-4.697×10^{-1}	-3.121
Mixed forest	3.917×10^{-1}	2.948×10^{-1}	7.586×10^{-1}*	1.482×10^{-2}	5.587×10^{-1}*	1.365×10^{-1}
Broadleaf forest	6.169×10^{-1}	1.196*	6.998×10^{-1}*	-3.045×10^{-1}	-1.980	-3.606×10^{-1}
Treed wetland	-9.025×10^{-1}	-1.436×10^{1}	-4.560×10^{-2}	-6.344×10^{-1}	-5.056×10^{-1}	-1.349×10^{1}
age		-8.996×10^{-3}*	4.889×10^{-3}*	2.396×10^{-2}*	1.655×10^{-2}	
agesquare				-1.320×10^{-4}*	-1.804×10^{-4}*	
elevation	3.091×10^{-2}*	3.583×10^{-2}*	-2.490×10^{-3}*		-6.481×10^{-3}*	
elevsquare	-1.158×10^{-5}*	-1.372×10^{-5}*				
slope	7.850×10^{-2}*	8.550×10^{-2}*	8.813×10^{-2}*	3.356×10^{-2}*		
aspect_cos	2.391×10^{-1}*		-1.847×10^{-1}*	2.508×10^{-1}	-5.513×10^{-1}*	
Dense conifer&age		1.239×10^{-2}*	-1.051×10^{-2}*			
Open conifer&age			1.350×10^{-2}			3.169×10^{-2}
Mixed forest&age						
Broadleaf forest&age					3.094×10^{-2}*	
Treed wetland&age						
Constant	-2.265×10^{1}*	-2.470×10^{1}*	8.228×10^{-1}	-3.384*	5.550*	-3.073*
AUC	0.705	0.764	0.699	0.642	0.844	0.554

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Table 2.6 – continued from previous page

Variables	Grizzly bear food items		
	cowberry	cranberry	crowberry
Dense conifer	1.058*	2.210×10^{-1}	–1.937
Open conifer	4.773×10^{-1}	3.696×10^{-1}	2.922×10^{-1}
Mixed forest	5.218×10^{-1}*	1.460*	-6.747×10^{-1}
Broadleaf forest	-9.347×10^{-1}*	2.230*	-1.375×10^{1}
Treed wetland	1.769×10^{-1}	-1.369×10^{1}	-1.416×10^{1}
age	1.824×10^{-2}*	-7.994×10^{-3}	1.560×10^{-2}*
agesquare		-8.223×10^{-5}*	6.614×10^{-5}*
elevation	8.624×10^{-3}*	6.585×10^{-2}*	4.577×10^{-3}*
elevsquare	-3.950×10^{-6}*	-2.686×10^{-5}*	
slope	-2.124×10^{-2}	1.038×10^{-1}*	
aspect_cos		1.766×10^{-1}	
DC&age	-7.114×10^{-3}		
OC&age			
MF&age	-8.816×10^{-3}*		
BF&age			
TW&age			
Constant	–4.940*	-4.298×10^{1}*	-1.256×10^{1}*
AUC	0.750	0.838	0.877

* significant at the $p \leq 0.05$ level and land cover class moderate conifer (LC2) used as a reference variable.

Table 2.7: Model coefficients for grizzly bear food resources in unforested habitat (See Tables 2.1 and 2.4 for abbrevations), the numbers inside the table are in scientific notation form.

Variables	Grizzly bear food items					
	saskatoon	clover	horsetail	cow-parsnip	dandelion	anting
Open wetland	-1.583×10^{1}	1.576×10^{-2}	4.642×10^{-1}	-1.319×10^{1}	3.751×10^{-1}	-6.208×10^{-1}
Herbaceous	-3.056×10^{-1}	1.094*	-6.200×10^{-2}	-4.088×10^{-1}	1.074*	-8.046×10^{-1}*
Barren land	-1.511×10^{1}	3.386×10^{-2}	5.700×10^{-1}*	−1.839	-4.607×10^{-1}	−2.557*
elevation	7.433×10^{-2}	1.298×10^{-2}*		2.200×10^{-2}*	1.153×10^{-2}*	
elevsquare	-3.177×10^{-5}	-4.790×10^{-6}*		-6.311×10^{-6}*	-4.416×10^{-6}*	-5.391×10^{-7}*
slope	1.718×10^{-1}*		-6.848×10^{-2}*			3.699×10^{-2}*
aspect_cos	-9.584×10^{-1}	1.508×10^{-1}	9.862×10^{-2}		-1.597×10^{-1}	-2.249×10^{-1}*
Constant	-4.848×10^{1}	-1.011×10^{1}*	1.333×10^{-1}	-2.108×10^{1}*	−8.717*	-9.141×10^{-1}*
AUC	0.850	0.635	0.624	0.705	0.658	0.636
	ungulate_c	other insects	sweet vetch	sweet vrtch_2	bearberry	strawberry
Open wetland	-1.572×10^{1}	-1.642×10^{1}	-1.211×10^{1}	8.930×10^{-2}	2.000×10^{-2}	6.417×10^{-1}
Herbaceous	-1.577×10^{1}	-1.608×10^{1}	1.278×10^{-1}	-2.925×10^{-1}	-3.280×10^{-1}	-1.977×10^{-1}
Barren land	7.211×10^{-1}	-1.589×10^{1}	−1.317*	−1.251*	-1.947×10^{-2}	-3.345×10^{-1}
elevation	1.677×10^{-2}*	-1.442×10^{-2}*	-1.274×10^{-2}*	-1.547×10^{-2}*	-1.338×10^{-2}*	-7.433×10^{-3}*
elevsquare	-4.958×10^{-6}		5.100×10^{-6}*	5.951×10^{-6}*	3.954×10^{-6}*	1.522×10^{-6}*
slope	-8.194×10^{-2}	3.254×10^{-1}*	2.506×10^{-2}		4.651×10^{-2}*	2.936×10^{-2}*

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Table 2.7 – continued from previous page

Variables	Grizzly bear food items					
	other insects	sweet vetch	sweet vrtch_2	bearberry	strawberry	
aspect_cos		1.370			$-7.038\times10^{-1*}$	$-3.625\times10^{-1*}$
Constant	$-1.686\times10^{1*}$	9.709	4.353	7.638*	8.610*	6.903*
AUC	0.712	0.923	0.812	0.785	0.696	0.700
	currants	raspberry	buffaloberry	huckleberry	blueberry	grouseberry
Open wetland	7.177×10^{-1}	-3.627×10^{-1}	-9.623×10^{-1}	3.927×10^{-1}	-1.470×10^{1}	8.988×10^{-1}
Herbaceous	-1.646×10^{-1}	2.398×10^{-1}	-1.069^{*}	-4.359×10^{-1}	-8.329×10^{-2}	-2.060×10^{-1}
Barren land	1.118×10^{-1}	6.214×10^{-1}	-1.256^{*}	-4.990×10^{-1}	-7.064×10^{-1}	1.256×10^{-1}
elevation	$3.043\times10^{-2*}$	$3.584\times10^{-2*}$	$-6.525\times10^{-3*}$		$-6.099\times10^{-3*}$	
elevsquare	$-1.156\times10^{-5*}$	$-1.381\times10^{-5*}$	1.199×10^{-6}			
slope	$8.799\times10^{-2*}$	$9.345\times10^{-2*}$	$9.327\times10^{-2*}$	2.610×10^{-2}		
aspect_cos	$2.476\times10^{-1*}$		$-1.959\times10^{-1*}$	2.140×10^{-1}	$-5.753\times10^{-1*}$	
Constant	$-2.201\times10^{1*}$	$-2.507\times10^{1*}$	4.645*	−2.582*	5.250*	−3.096*
AUC	0.698	0.692	0.692	0.573	0.817	0.517
	cowberry	cranberry	crowberry			
Open wetland	-3.218×10^{-1}	3.166×10^{-2}	3.511*			
Herbaceous	$-8.052\times10^{-1*}$	-4.986×10^{-1}	-1.686×10^{1}			
Barren land	-2.581×10^{-1}	-6.792×10^{-1}	-1.756×10^{1}			

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Table 2.7 – continued from previous page

Variables	Grizzly bear food items		
	cowberry	cranberry	crowberry
elevation	$9.840{\times}10^{-3*}$	$6.307{\times}10^{-2*}$	
elevsquare	$-4.358{\times}10^{-6*}$	$-2.638{\times}10^{-5*}$	$1.444{\times}10^{-6*}$
slope	$-2.491{\times}10^{-2}$	$1.383{\times}10^{-1*}$	
aspect_cos	$-1.023{\times}10^{-1}$	$2.508{\times}10^{-1*}$	
Constant	-5.081^{*}	$-3.969{\times}10^{1*}$	-8.038^{*}
AUC	0.709	0.787	0.885

* significant at the $p \leq 0.05$ level and land cover shrub used as a reference variable.

2.3.2 Distribution of grizzly bear food groups

Green vegetation resources were predicted to occur according to environmental factors. They had a strong response to age-land cover interaction. The occurrence of green vegetation resources were predicted to be in the high elevation areas. Fruit resources were more common in the higher slope and forested habitat; however, they were predicted to occur in the lower elevation as well. Especially buffaloberries were predicted to be in old mixed forests at lower elevation and not in young dense conifer forests. The root resource, which is represented by one of the sweet vetch species, was likely to occur in the high elevation area in the older conifer forest. Animal matter resources were like green vegetation resources, especially anting and moose resources were affected by environmental factors. Unlike anting, moose were associated with treed wetland environments. (See table 2.5 for group representations and figures 2.3, 2.5, 2.4 and 2.6 occurrence of food groups in the study area.)

As seen in the figures 2.3, 2.4, 2.5 and 2.6, root resources occurred in the west portion of the study area, which is a mountainous area. On the other hand, fruit resources occurred throughout the study area, but did not overlap root recourses. Green vegetation resources were likely to occur across the study area at a low rate.

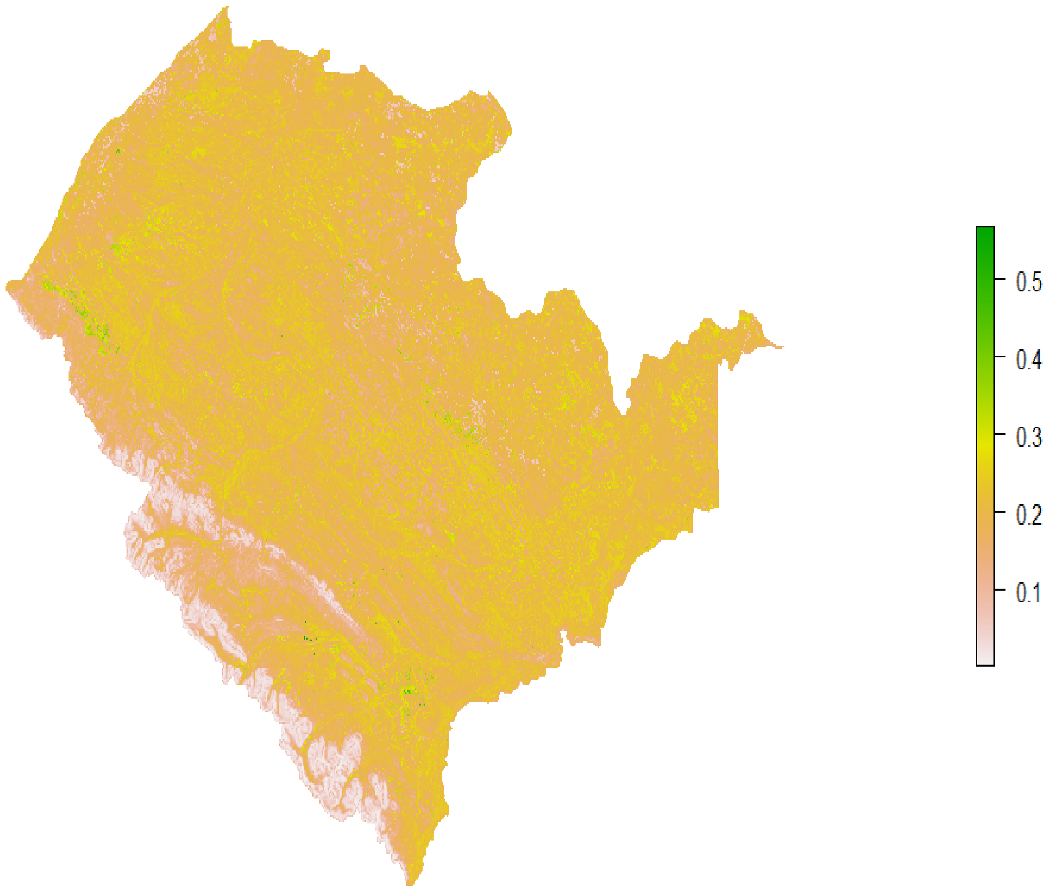

Figure 2.3: Predicted probability of green vegetation resource in the study area

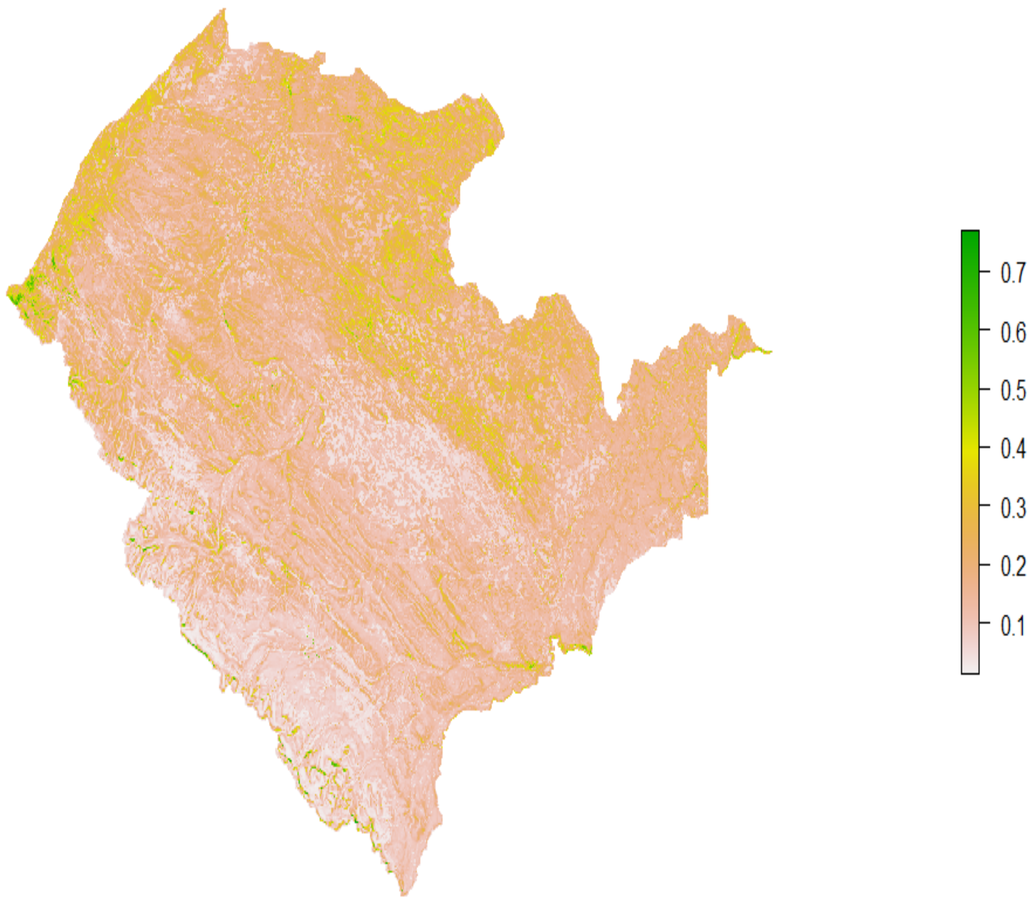

Figure 2.4: Predicted probability of fruit resource in the study area

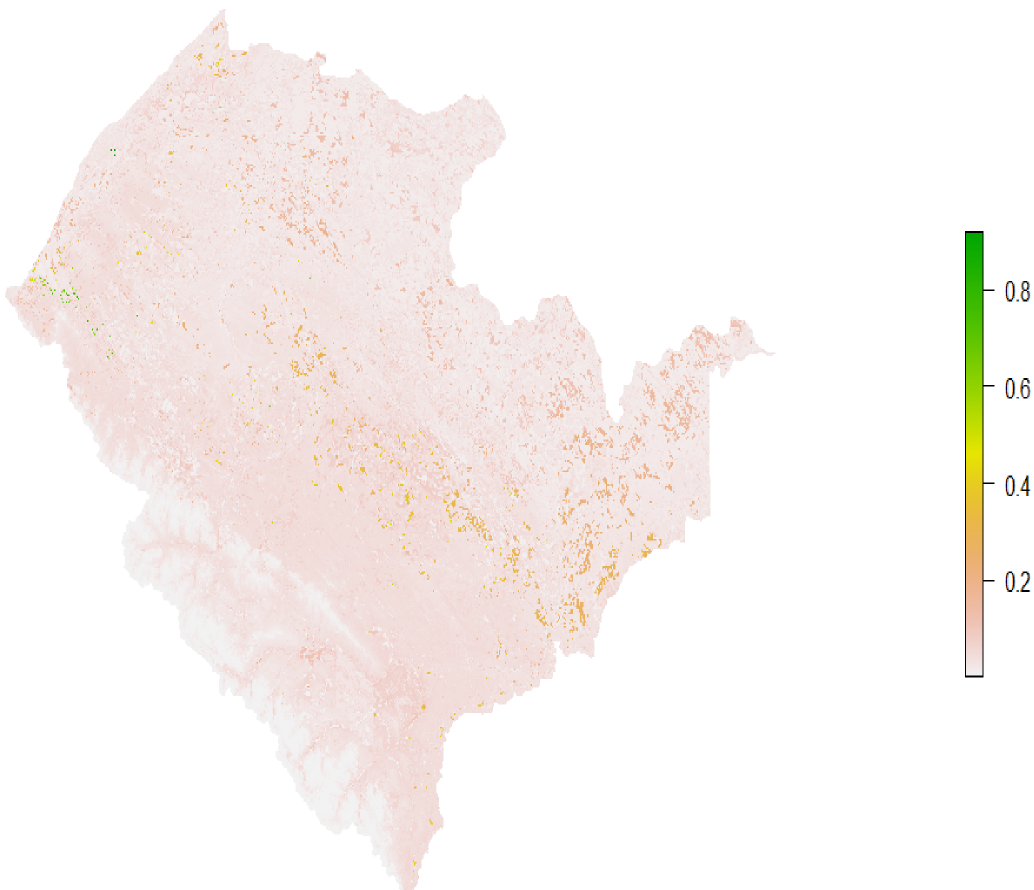

Figure 2.5: Predicted probability of animal matter resource in the study area

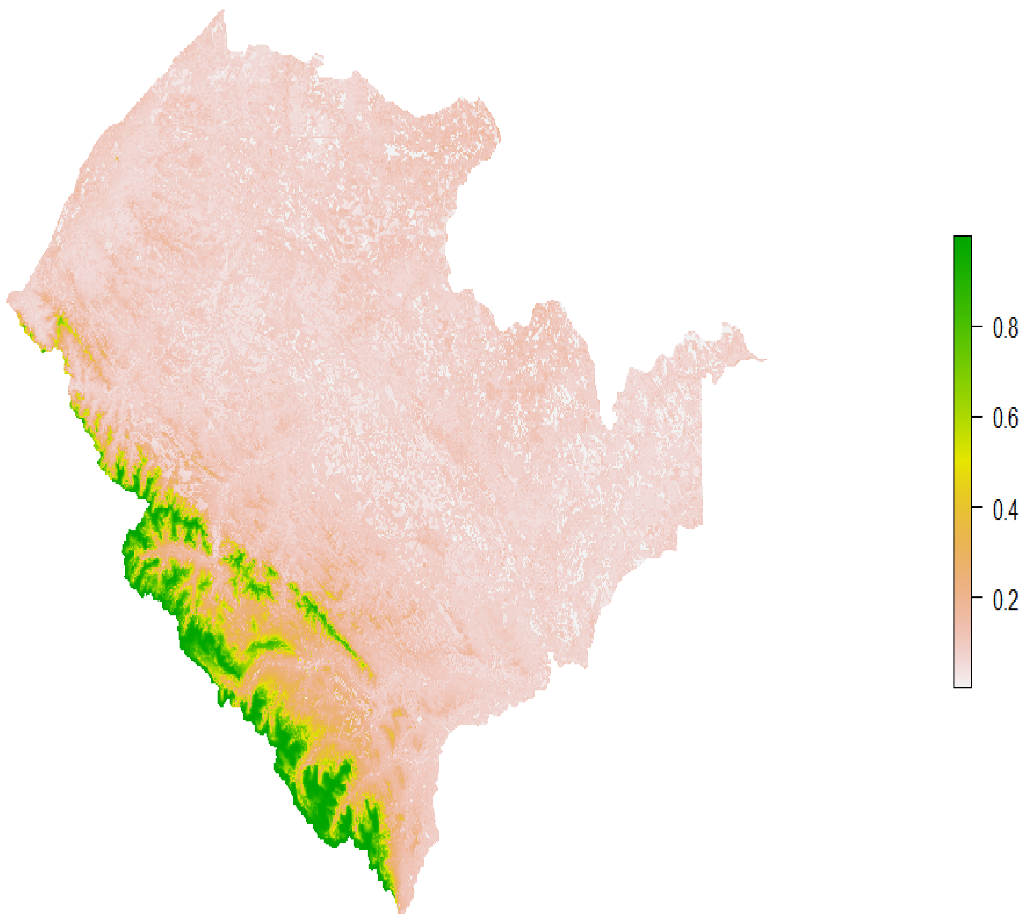

Figure 2.6: Predicted probability of root resource in the study area

2.4 Conclusion

Grizzly bear food items occurred at different levels in the study area. The occurrence of food species, which affects the selection of habitat by grizzly bears, was dependent on the environmental variables in the foothills of west-central Alberta (Nielsen et al., 2004b, 2010). My findings support those of Nielsen: forest type and age along with elevation were the strongest predictor variables of occurrence of grizzly bear food resources. Also, interaction variables had significant effect on the occurrences of grizzly bear food resources. The selection of disturbed areas by grizzly bears differs depending on age (Nielsen et al., 2004a; Stewart et al., 2012). Our study showed the occurrence of food resources in the forested habitat depends on forests age too. On the other hand, age - forest type interaction variables had different trends on the occurrence of GBFR than age and forest type individually. Interaction variables were the differences between this study and Nielsen et al. (2004b) and were the main reason for estimating the models. Age - forest type interaction variables help to make the models a better fit with stand age driven forest planning models. That is why forest type - age should be linked with management regimes which aim to protect grizzly bear population.

There were two groups of land cover, which are forested land cover group and unforested land cover group. Models were estimated for forested land cover and unforested land cover; because, land cover types were the critical predictors for GBFR. Also, there is a cycle between unforested cover types and forested cover types. Unforested cover types could become forested cover types after a certain time or vice-versa. For example, barren land becomes either shrubs area or stay as is. After a certain amount of time, shrubs area either grows into forested area or stays as is. On the other hand, forested area becomes barren land after harvest. These cycles proceed continuously. Even there is a transition between land covers, there is no mechanism in the models developed here to allow for a transition between land cover types, especially barren land and forested land covers. This is necessary because much of the area classified as barren land is recent clearcuts. And, clearcuts are likely to regenerate. This will be discussed in the next chapter.

The weighted occurrence of grouped food items were calculated to link them with forest management plans. The weighted occurrence of food items by foraging type is necessary to understand the importance of each pixel for grizzly bear habitat. There could be different relations between timber value and grizzly bear individual food items or grizzly bear grouped food items. This will be discussed in the next chapter.

I was unable to obtain the Alberta Vegetation Inventory for the study area while I was estimating the models. If there had been, I could have used different environmental variables and estimated more detailed models to predict occurrence of GBFR.

These results will be used for deciding the forest management plan for the study area which optimizes GBFR and forest harvesting. That is how managers will be able to follow sustainable forest approach while protecting grizzly bears in the study area.

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Chapter 3

Developing trade-off relationships between grizzly bear food resources and timber harvesting in west-central Alberta

3.1 Introduction

Biodiversity has become a globally important topic in recent decades. Habitats for the world's biological diversity are mainly provided by forest ecosystems (Battles et al., 2001). Natural and anthropogenic disturbances, such as fire and timber harvesting, have significant and long lasting effects on forest ecosystems (Gaulton et al., 2011; Dhital et al., 2013). Scientists working on forest management focus their study on topics of sustainable forest management. In Alberta the government regulates its policy to support sustainable forest management (ESRD, 2014). Due to this government policy, land managers are expected to maintain biological diversity while achieving economic goals (Delong and Tanner, 1996). This necessity is illustrated by balancing habitat for wildlife and wood supply. Moreover, land managers are required to understand habitat use by wildlife and changes in land cover in response to forest management (Berland et al., 2008); therefore, understanding the effects of forest management on the forest ecosystem is critical (Brown et al., 2007).

The grizzly bear (*Ursus arctos horribilis*) is listed as a *threatened species* in Alberta and is a flagship species for conservation due to their sensitivity to human disturbances and slow reproductive rates (Alberta Grizzly Bear Recovery Plan 2008-2013, 2008). Blanchard (1983) showed that grizzly bears use both closed forest and forest clearing habitats because of differences in availability of grizzly bear food resources (GBFR). Availability of GBFR changes following forest disturbance and between habitats over the different seasons and time (Nielsen et al., 2004c; Berland et al., 2008). Availability and predictability of food resources determines grizzly bear habitat quality. Habitat quality effects home range size, which determines the survival and reproduction of bears (McLoughlin et al., 2000).

Numerous studies consider ecological or economic issues of disturbances resulting from forest harvesting (Battles et al., 2001; Arthur et al., 2004; Nielsen et al., 2004a; Brown et al., 2007; Berland et al., 2008; Nielsen et al., 2008). However, there is a growing number of studies that consider both economical and ecological issues simultaneously. Battles et al. (2001) argues that forest management regimes have an effect on plant species diversity depending on the land cover type, silvicultural intervention, and the amount of harvesting and environmental characteristics of the area. Brown et al. (2007) predicts the impacts of different forest management strategies on specific animal species, woodland caribou, food resources. Nielsen et al. (2004a), Berland et al. (2008) and Nielsen et al. (2008) discuss the impact of landscape disturbances on grizzly bear habitat use. They conclude that grizzly bears do not avoid disturbed areas in the foothills of Alberta and actually use disturbed areas more consistently than the undisturbed area. The bears' use of disturbed areas changes, however, depending on the forage season and the area of disturbances. Arthur et al. (2004) explains the trade-offs between overall species protection and protection of endangered species for the certain area.

Other studies, such as those by Calkin et al. (2002) and Dhital et al. (2013), consider both the ecological and economic concerns. Calkin et al. (2002) develops a way to estimate wildlife persistence and timber value, using an heuristic optimization algorithm to identify production possibility frontier between net present value of timber harvesting and the persistence of the northern flying squirrel. Dhital et al. (2013) investigates whether timber supply, aboriginal land use, and woodland caribou habitat can be maintained. Conserving woodland caribou habitat and considering the potential land use by aboriginals decreased the timber supply depending on different management regimes (Dhital et al., 2013). A study completed by Toth et al. (2006) examined the trade-offs between the net present value (NPV) and wildlife habitat with six different bi-criteria models and compares the results of these analyses depending on the number of efficient solutions they could identify and the speed with which these solutions were identified. Additionally, studies conducted by Montgomery et al. (1994) and Polasky et al. (2004) discuss trade-offs between economic value and species diversity. Montgomery et al. (1994) examines the trade offs between probability of survival of the northern spotted owl and harvesting using three different management strategies. Polasky et al. (2004) examines trade-offs between production and biodiversity at local and global levels, and conclude that certain species persist on unmanaged forests, while others prefer managed forests. Polasky et al. (2004) examined not only habitat area, but also habitat quality and environmental characteristics of the area and how these factors affected production possibility frontier and trade-offs between biodiversity and production value.

A production possibility frontier is a graph representing the maximum production level of one variable for specified level of the other. The idea behind the production possibility frontier is that if you increases the production level of one variable, it results with decrease the production level of other variable. Any point on the production possibility frontier indicates an efficient solution for combination of two variables. In other words, an efficient solution implies that increasing one output can come only at the cost of decreasing the other. The differences between two points on the production possibility frontier gives the trade-offs between two given variables. Any point above the production possibility frontier can not be achieved with the current problem exploring with the resources. However, any points below the production possibility frontier represents inefficient use of the resources. Although many studies exist for trade-offs between wildlife species and production value, no study yet exists to analyze the production possibility frontier and trade-offs of timber value and grizzly bear habitat. My thesis addresses this gap in knowledge and application.

The Yellowhead population unit in west-central Alberta is in the range of grizzly bears where land managers seek to maximize timber harvest value while maintaining biodiversity. The forests in the study area are mostly managed by private companies for timber production. Management plans by private companies aim to maintain biodiversity by reducing forest fragmentation, minimizing road density and road length, and retaining forest cover types (West Fraser Mills Ltd. (Hinton), 2014). Here we analyze the effects of the forest harvesting on the grizzly bear habitat in order to determine suitable forest management plans for biological diversity and economical goals. The intent is to produce models for timber production and grizzly bear food resources to evaluate how different levels of harvesting affect grizzly bear habitat quality. More specifically, we explore models for grizzly bear food resources and timber harvesting by incorporating these models into a single optimization framework using a linear programming based on a forest planning model. The two specific objectives of this study are as follows: (1) develop a production possibility frontier by maximizing the timber harvest volume or net present value subject to amount of grizzly bear food resources, (2) examine the trade-offs between the value of timber harvest and predicted occurrence of grizzly bear food resources. Determining the trade-offs between timber production and grizzly bear food resources will aid land managers in planning forest harvesting while protecting the grizzly bear habitat.

3.2 Materials and methods

3.2.1 Study area

The study area comprises an approximately 535,000 ha area in the Yellowhead population unit of the Rocky Mountains (Figure 3.1). The area encompasses Whitehorse Wildland Provincial Park, Brazeau Canyon Wildland Provincial Park, and the towns of Hinton, Robb and Cadomin. Provincial parks cover 19,000 ha, which is 3.7% of the study area. Elevation varies from 946 to 2887 m. Land cover is dominated by conifer forest. A small portion of the land is covered with mixed and broadleaf forest, regenerated forest, wetland and rocks. The forest age in the study area ranges from 6 to 425 years old. Yellowhead population unit was comprised of protected areas in national and provincial parks, and areas actively managed for resource extraction in forestry, mining, oil and gas. Management of the protected area is divided between the provincial and federal government for recreational use, while the rest of the forested area is managed by private companies. The study area is part of the Yellowhead grizzly bear population unit and I am focusing on the interaction between timber management and grizzly bear habitat, specifically food resources that have been found to predict habitat use by bears and index habitat quality (Nielsen et al., 2004a, 2010).

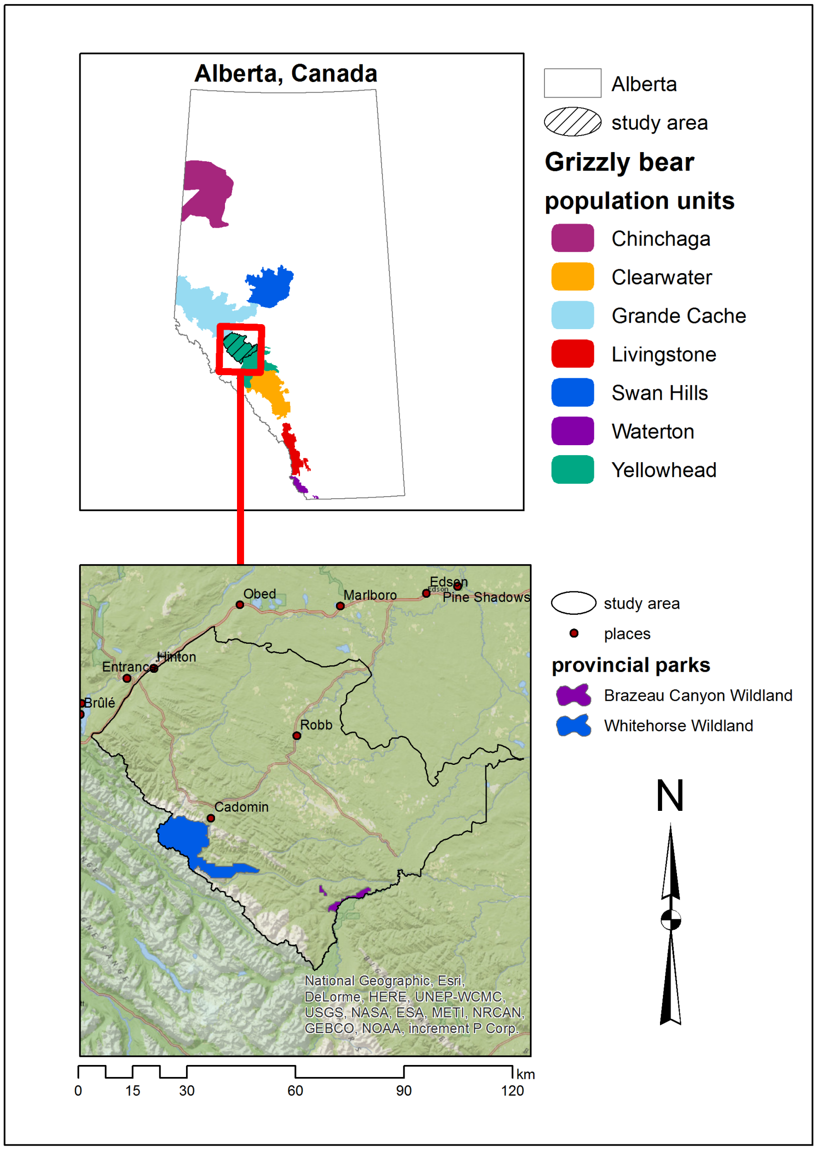


Figure 3.1: Map of the study area in west-central Alberta, showing towns, study area boundary and grizzly bear population units of Alberta, Canada.

3.2.2 Model formulation

Six basic models were developed with the same data components. The models are Model II representations of the timber harvest scheduling problem as described by Johnson and Scheurman (1977). They were developed using the Woodstock component of the Remsoft Spatial Planning System (Remsoft Inc., 2013). Linear programming (LP) is a general optimization technique that allocates the resources to competing activities (Buongiorno and Gilless, 2003). Woodstock is a flexible modelling system for forest management which allows the user define all the actions and outputs (Walters, 1993). Woodstock generates LP matrices using the basic Model II structure, then LP matrices are into LP solver (Walters, 1993). The MOSEK LP (Andersen and Andersen, 1997) solver was used in this study. Conversion routines are written into the report file that can be easily interpreted by the user.

Data components

Land cover type, elevation, aspect and slope were used to describe the study area characteristics. Details for how these variables were obtained can be found in the previous chapter. Details for how land cover types were coded according to their vegetation structure can be found in McDermid et al. (2009). Land covers were classified into 13 classes and then aggregated into six (6) categories. Elevation was divided into eight (8) groups, and also, aspect and slope were grouped into four (4) classes. See Table 3.1, Table 3.2 and Table 3.3. Ideally, Alberta Vegetation Inventory data would be used for analyses, but it was unavailable.

Table 3.1: Names of land cover variables, their abbreviations and the category they were aggregated in. Forested and unforested classes mean the land cover could be harvested or not, respectively. Some of the land cover types were grouped into two or three different aggregation classes.

Land cover name	Abbreviation	Aggregate name
Dense conifer forest	DC	forested - conifer(con)
Moderate conifer forest	MC	forested - conifer(con)
Open conifer forest	OC	forested - conifer(con)
Mixed forest	MF	forested - mixed - other(ot)
Broadleaf forest	BF	forested - deciduous(deci) - other(ot)
Treed wetland	TW	unforested
Open wetland	OW	unforested
Shrubs	Sh	unforested
Herbaceous	Herb	unforested
Barren Land	BL	unforested
Water	Water	unforested
Snow/Ice	Snw/I	unforested
Rocks	Rock	unforested

Table 3.2: Elevation class codes and the class ranges in meters.

Elevation class code	Elevation range (m)
1000	946 - 1000
1125	1001 - 1250
1375	2151 - 1500
1625	1501 - 1750
1875	1751 - 2000
2125	2001 - 2250
2375	2251 - 2500
2501	2501 - 2887

Table 3.3: Aspect and slope class codes and their ranges in degrees.

Aspect class code	Aspect range (°)	Slope class code	Slope range (°)
N	0 - 45 , 316 - 360	8	0 - 15
E	46 - 135	23	16 - 30
S	136 - 225	38	31 - 45
W	226 - 315	46	46 - 60

Table 3.4: Names of GBFR used in the analyses, their common names, abbreviations and the grouped name they belong in.

Food items name	Common name	Abbreviations	Group name
Equisetum spp.	horsetail	equi	green vegetation
Heraculum lanatum	cow-parsnip	hela	green vegetation
Trifolium spp.	clover	clover	green vegetation
Shepherdia canadensis	buffaloberry	shca	fruit
Vaccinium membraneceum	huckleberry	vame	fruit
Hedysarum alpinum	sweet vetch	hedy	root
Ants	mostly ants	anting	animal matter
Ungulate carcass	mostly moose	ungulate_k	animal matter

Models were constructed for each of 21 food resources and four (4) food resource groups identified in Chapter 2. However, only eight (8) of the most important grizzly bear food resources and their groups are presented here (Table 3.4). Detailed model construction for 21 of the grizzly bear food resources can be found at the University of Alberta Education and Research Archive at http://hdl.handle.net/10402/era.40642.

Models were planned for a 200 year time horizon with 10 year intervals using 8 of the grizzly bear food items and four (4) grizzly bear food resource groups. Models had six key components: landscape themes, development types, yield components, actions, transitions, and outputs. Landscape themes provided the method of classifying and describing the characteristics of the area. Development types were derived through the combination of landscape themes: land cover types, elevation, aspect, slope, management type and originated from land cover types along with the age classes. The maximum age that any development type may reach before senescence or replacement by another development type was 250 years, except in the case for shrubs, herbaceous, barren lands, water, snow/ice, and rocks. Water, snow/ice, and rocks had no age associated with them. Shrubs, herbaceous and barren land complete their lifespan in a 10 year time horizon and then become other development types.

The yield section of the models represents the yield tables of the forested land covers, which associates the forest volumes with the development types, and GBFR (See Appendix B). Yield tables for the forested cover types were obtained from Alberta timber yield tables generated by Armstrong (2014b). They were used to track volume of the forested area per hectare. The yields tables of the GBFR were derived by the application of the regression models obtained in the previous chapter. These tables show the predicted probability of occurrence of GBFR for a 20×20 m plot within the 30×30 m pixel. Harvesting action is defined as a clear-cut followed by natural regeneration if the volume of the forested area per hectare was greater than or equal to 50 m^3/ha.

Landscape cover has been changing over the years because of the natural and anthropogenic effects. For instance, a forested area may become barren land or shrubs after harvesting, then shrubs may become conifer forest after a certain number of years. There are also different combinations of transitions between land cover types. Therefore, before constructing the management plan for a long period of the time, managers need to consider what type of land cover classes they have and how these transitions take place. The transition section therefore is one of the key concepts in the models, and also crucial to understanding forest dynamics. The transition section describes how the development types will respond differently to defined actions over a 10 year interval. Also, the transition section reports the area that has restricted access.

In this study, water, snow/ice, rock, open wetland and herbaceous areas remain "as is" until the end of the management plan. There were no actions applied to these areas. Much of the land classified as "barren land" has been recently harvested for timber production. A mechanism was needed to represent forest regeneration in these sites. However, yield tables were not informed for barren land. That is why I used some transition mechanism from barren land to other development types.

Any area that had grater than 6% of tree vegetation and smaller than 25%

of shrub cover was interpreted as shrub (See McDermid et al. (2009) for detailed explanation). Shrub areas could grow into other development types over years, and there was no yield table associated with this transformation, just as there is not for barren land. Transition mechanism from shrub land to other development types were therefore needed.

According to Alberta timber yield tables (Armstrong, 2014b), conifer and deciduous tree species reach a five (5) meter height in an average of twelve (12) and eight (8) years, respectively. Also, any vegetation cover, which has a five (5) meter height or less, is called shrub land depending on the vegetation-cover/area ratio. Considering plant species growth characteristics and the planning horizon intervals, there was a high chance for barren land to grow into a shrub area depending on the area site quality (barren land and shrub area were considered to have the same site quality). I assumed that in every 10 year period 90% of the barren land transitions to shrub, while 10% stay as barren land.

The transition from shrub to other development types was set depending on the growth characteristics of the tree species and/or area ratio between development type and shrub land. For example, shrub lands that originated from conifer forest transitions to dense conifer, moderate conifer, and open conifer with a 40%, 40% and 5% frequency, respectively, and remain as shrub with a 15% frequency. The ratio of the area of conifer development types and shrubs was around 3. I set the same ratio for the transition mechanism, which was $40/15 = 2.6$ and rounded up to 3. The transition numbers used here are the first approximation numbers (see figure 3.2 for general structure of transitions from forest to barren land or shrub, or vice-verse). A more precise estimation of transition percentages can be determined in the future by looking at yield tables or growth models of the species.

The output section was the basis for evaluating and comparing the management regimes. This section was set to track important reportable variables, such as inventory being defined to track the probability of finding grizzly bear food items in all areas. By setting the inventory component, the equivalent optimum probability of finding food items per 20×20 meter plot within the pixel could be tracked. The equivalent optimum probability of finding a particular food item can be calculated by dividing the total amount of probability of food item by total area.

The optimize section allows the formulation of the model as an LP model. This section was crucial for making and measuring the differences of the models of

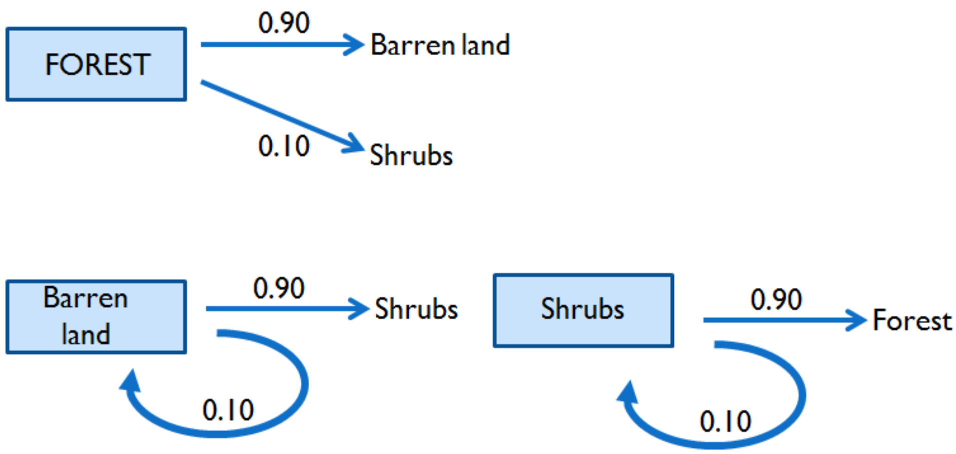


Figure 3.2: The transitions mechanism used in the models between development types, numbers represent the transition percentage at the arrow direction. Transitions from forest occur at the time of harvesting. Transitions from barren land and shrubs occur at the end of each period.

the study because the objective function was represented in the optimize section. Two different objective functions were used for models: maximize harvest volume and maximize net present value. Maximizing harvest volume was used because of the Alberta Government's volume-based harvesting policy. Maximizing the net present value objective function was employed because it may provide a better representation of the value of the forest for timber production. There were therefore six optimization problems with two main objective functions that will be explained below.

Models for maximizing volume

An optimization model was constructed for maximizing the total volume harvested subject to three different sets of constraints represent the amount of GBFR available at the end of each period relative to the starting condition. The three different sets of constraints were:

- occurrence of each of the eight (8) food items separately
- occurrence of each of the four (4) groups separately
- occurrence of all eight (8) food items simultaneously

For each model, the timber harvest constraint was set to be an even flow across periods because of the sustainable forestry policy of the Alberta Government.

The predicted probability of occurrence of grizzly bear food items or grouped food items was constrained to be above a specified minimum level in each period. The minimum level was set as a percentage of the initial value for the food items. The initial value of food items is based on the probability of finding the food item within the study area. The total volume of the timber harvesting was calculated by multiplying the total harvested area by total volume. The amount of GBFR were constrained to be at least a percentage of the amount available at the beginning of the planning horizon. The fixed percentage varied between 100 and 75%, in 5% increments.

Models for maximizing net present value

A similar set of models were developed where the objective was to maximize net present value (NPV) instead of total harvest volume. Harvesting constraint and food items constraints were the same as models for maximizing harvesting volume.

The NPV was obtained from subtracting discounted revenue from discounted cost. Discounted revenue was calculated by multiplying the discount factor by the harvesting revenue. Discounted cost was calculated from adding the discounted harvesting cost and the discounted harvesting revenue. The wood price at the mill was \$50/m^3, the fixed cost of logging was \$2500/ha and a variable cost of logging was \$15/m^3. Reforestation was \$800/m^3 for a conifer forest. There was no reforestation cost for other forested types because they do not require any silvicultural activities for regeneration. Also, the discount factor was for a 5% interest rate for a 10 year period in the middle of the period. The prices for variables were obtained from Armstrong (2014a). I estimated the percentage of initial habitat value for food items as ranging from 100 to 75.

The production possibility frontier is a graph representing various combinations of amounts of timber harvest volume and GBFR or amount of net present value and GBFR. The production possibility frontiers were created for six optimization problem depending on the models result. At each model, harvesting volume or net present vale was calculated depending on the specified amount of GBFR. Fixed amount of GBFR was set to be at least a percentage of the amount available at the beginning of the planning horizon. The percentage varied from 100 to 75%, in 5% intervals. For example, to draw production possibility frontier for maximizing harvest volume subject to the occurrence of the individual food items, model was run for each of the eight (8) food items amount constrained to be at least 100%, then 95% and so on separately. The production possibility frontier was generated with the result of these runs. All production possibility frontiers were created with the similar perspective.

3.3 Results and discussion

3.3.1 Maximize the harvesting volume

Figure 3.3 shows the production possibility frontier constructed for the eight individual food items considering harvest volume and proportion of initial GBFR levels as the competing outputs. Figure 3.4 shows the same for the four food groups. Figure 3.7 presents the production possibility frontier constructed for the case where all eight food items were simultaneously constrained to be at least a fixed proportion of their initial levels. The tables used to construct these figures are presented in Appendix C. There was no feasible solution to maximize harvesting volume while keeping the initial value of all grizzly bear food resources over the planning horizon. Maximum harvesting volume was obtained by keeping the 75% from the initial value of the grizzly bear food resources or not considering grizzly bear food resources.

The harvesting volume decreased by 6×10^5 m^3 from its maximum value when anting was kept at a 100% of its initial value in the model. However, maximum volume was obtained while keeping 95% of the initial value of anting. The harvesting volume decreased by 30% from its maximum value when buffaloberry or horsetail was kept at a 100% in the model; however, the harvesting volume obtained its maximum value while keeping 90% of the buffaloberry or the horsetail separately.

Clover and ungulate carcass were the food resources least affected by the harvesting volume, even when they were separately included in the model at a 100 %. The reason could be that clover and ungulate carcass occurred in the young forested areas (see previous chapter for details).

The solution was infeasible for maximizing harvesting volume and keeping 100% of huckleberry food resource, possibly because of the negative relation between moderate conifer forest type and occurrence of huckleberry. Moderate conifer forest occupies 40% of the study area and huckleberries do not occur under the moderate conifer forest. On the other hand, maximum harvesting volume was obtained when keeping the 85% of the huckleberry vegetation.

Grouped food resources were less sensitive to harvest than individual food resources. The maximum harvesting level was obtained while keeping 95% of the initial value of animal matter, green vegetation or root resources separately. The animal matter resources decreased the maximum harvesting level by 1% when it was kept in the model at 100%. The green vegetation group decreased the maximum harvesting level by 7% when it was kept in the model with initial predicted occurrence of green vegetation groups in the area. Fruit resources decreased the maximum harvesting level by 10% when it included at 100% in the model. However, maximum harvesting level was obtained while keeping 90% of its initial value.

As discussed in Nielsen et al. (2008), forest harvesting has less effect on the grizzly bear population and grizzly bears do not avoid harvested areas (Nielsen et al., 2004a; Berland et al., 2008). Forest harvesting had a small effect on the occurrence of grizzly bear foods, especially grouped food resources. Managers could achieve maximum levels of harvest volume by keeping 95% of the initial occurrences of grouped food resources (figure 3.4). Figures below show different shaped trade-offs curve of individual or grouped food resources (actual number used to construct these figures represented in appendix C).

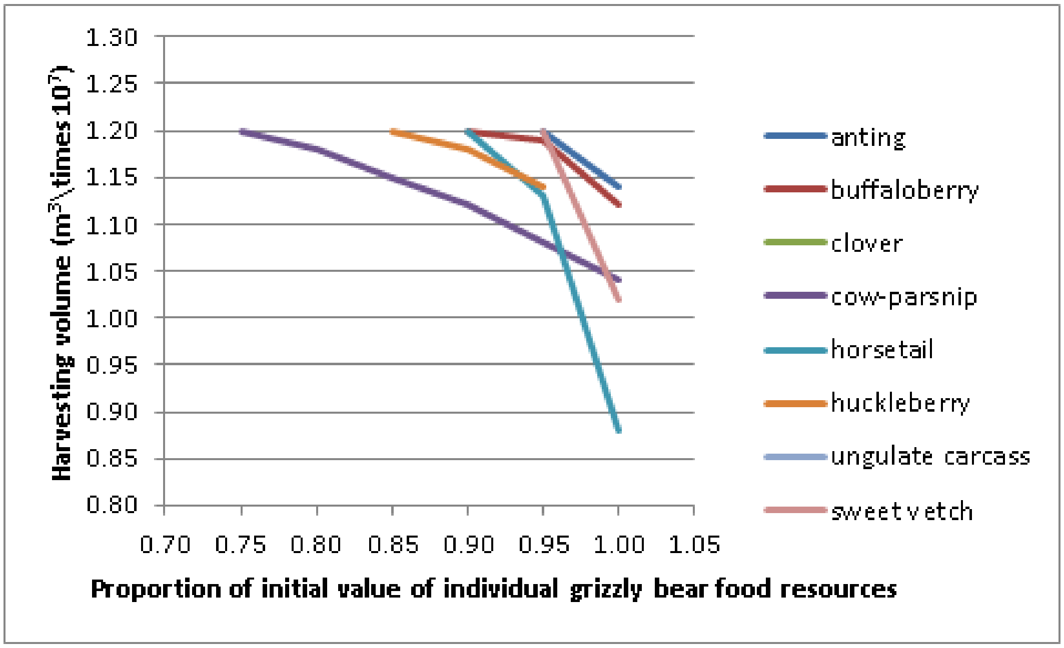


Figure 3.3: Production possibility frontier of harvesting volume and grizzly bear individual food resources.

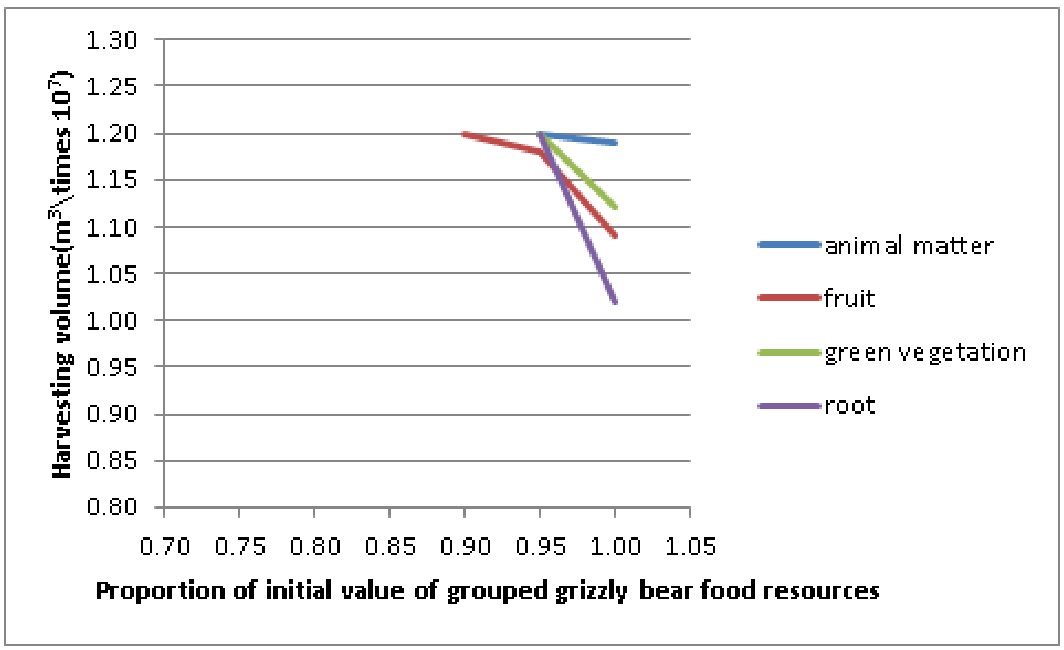


Figure 3.4: Production possibility frontier of harvesting volume and grouped grizzly bear food resources.

3.3.2 Maximize the net present value

Maximizing the net present value and maximizing the harvesting volume produced similar results. There was no feasible solution to maximize the net present value while keeping all GBFR according to their initial values. However, the maximum net present value was obtained by keeping the 80% of the initial value of all GBFR. Net present value and harvesting volume were $\$5.65\times10^8$ and 1.19×10^7 m^3, respectively, when the objective was to maximize NPV. Tables in the appendix C show the results for optimization of the net present value and grizzly bear food (individual or grouped) resources.

Anting or sweet vetch reduced the net present value when 100% of its initial value was included in the model. However, maximum net present value was obtained when considering 90% of the anting or sweet vetch initial value. Net present value decreased by 8% from its maximum value when buffaloberry was retained at 100% in the model. This result could be because of the positive relation between age and buffaloberry. Buffaloberry occurred in the mature conifer forest (see previous chapter for details). Keeping 100% of the buffaloberry population decreased the harvesting volume and net present value. However, the maximum net present value was obtained while keeping 90% of the buffaloberry population.

Clover was the only food resource that did not effect the net present value even when it was included as 100% in the model. The solution was infeasible for maximizing net present value and keeping 100% of huckleberry resources because huckleberries appeared in the old forested areas. On the other hand, the maximum net present value was obtained when including the 80% of the huckleberry vegetation in the model.

The green vegetation group decreased the net present value level by 10% when it was kept in the model with the initial predicted occurrence of green vegetation. Fruit or roots also decreased the harvesting level by 10%. On the other hand, animal matter food groups deceased $\$4.6\times10^7$ from net present value when retaining the animal matter initial value.

Zager et al. (1983) argued that disturbances, such as wildfire or forest harvesting, have a significant negative effect on grizzly bear habitat and food resources. We found that maximizing the net present value (NPV) seemed to have a minimal effect on occurrence of the grizzly bear habitat (individual or grouped food items).

Figures 3.5, 3.6 and 3.7 show the production possibility frontier for net present value and amount of grizzly bear food resources, and different shaped trade-offs curves (actual number used to construct these figures represented in appendix C).

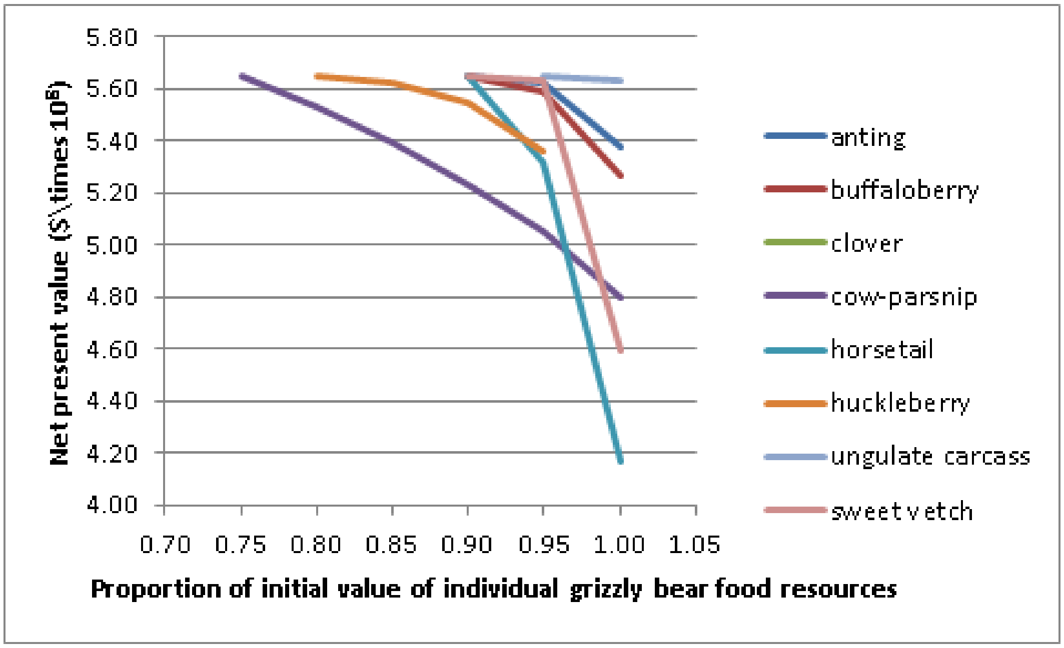


Figure 3.5: Production possibility frontier of net present value and grizzly bear individual food resources.

As seen in the figure 3.7, maximum net present value can be reach by keeping 80% of the all grizzly bear food resources simultaneously. Also, maximum harvesting volume can be obtained by dropping 25% of the initial value of all grizzly bear food resources. On the other hand, maximum harvesting value can be obtained by dropping 10% of initial value of individual food resources. There is a bigger trade-offs between amount of all grizzly bear food resources and harvest value than between amount of individual food resources and harvesting value. However, as discussed in chapter 2, individual grizzly bear food resources has different level of importance in grizzly bear diet. Given this importance, manager therefore could consider trade-offs between amount of individual food resources and harvesting value when deciding the harvesting. There is almost no impact of harvesting on the occurrences of individual grizzly bear food resources if sustaining 90% of initial value individual food resources is acceptable.

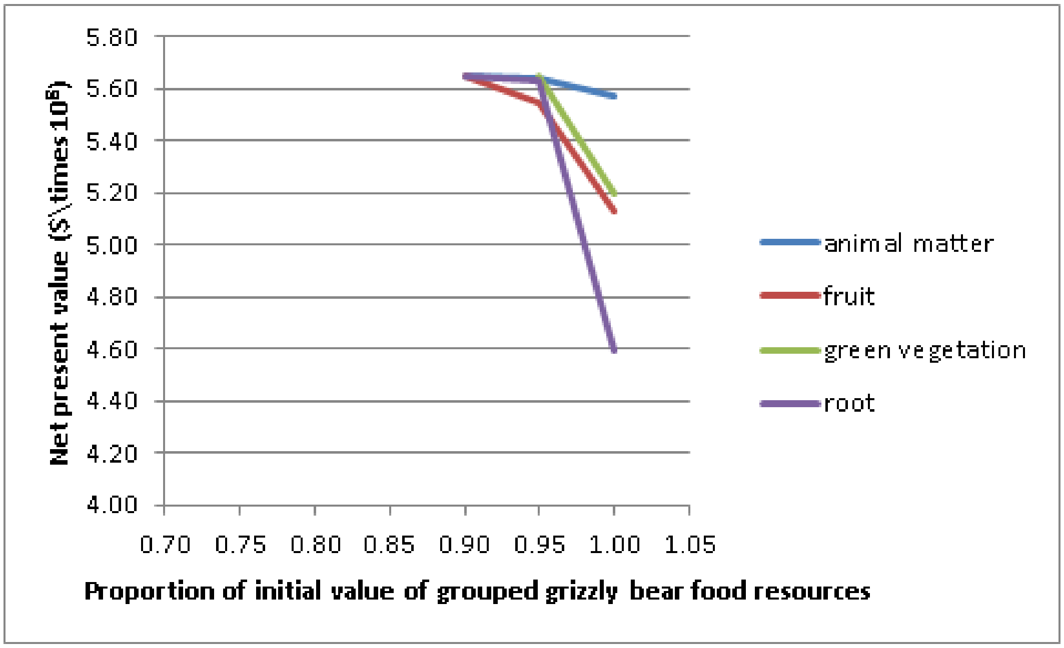


Figure 3.6: Production possibility frontier of net present value and grouped grizzly bear food resources.

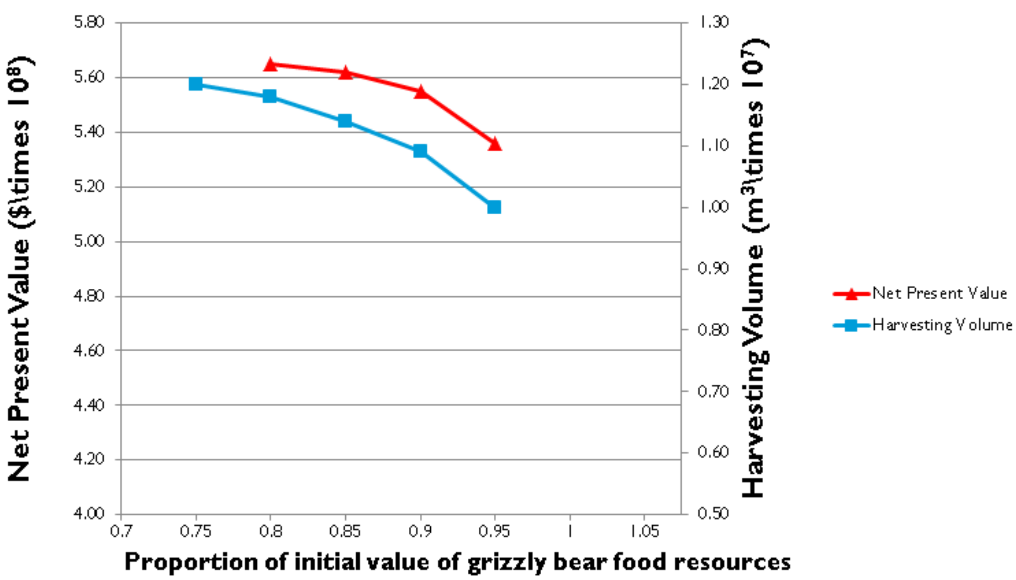
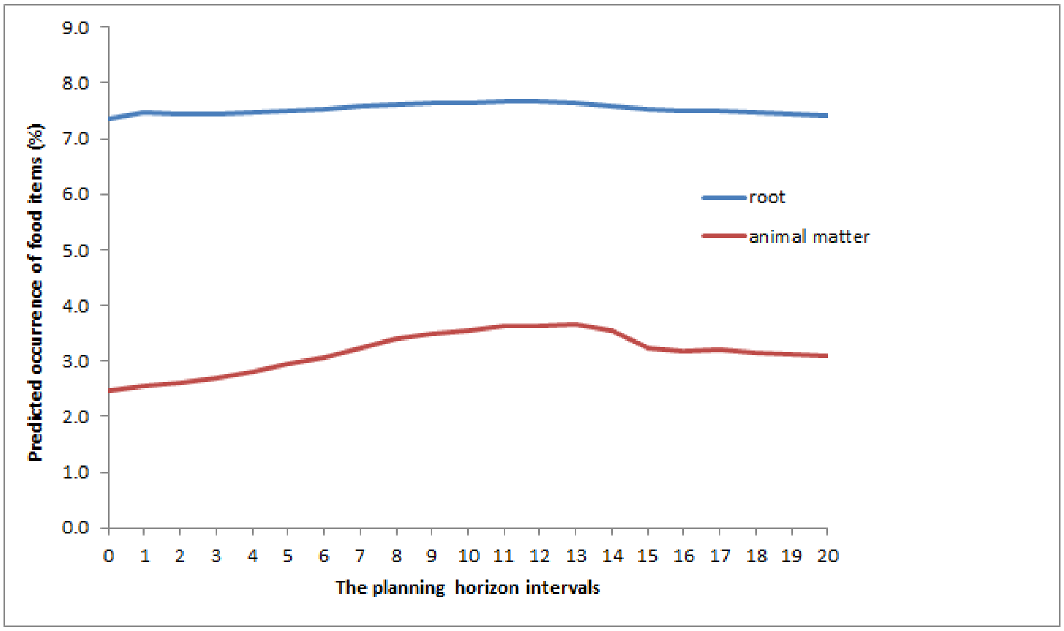


Figure 3.7: Production possibility frontier for harvesting value and grizzly bear food resources simultaneously. Net present value on the left Y axis and harvesting volume on the right Y axis.

Grouped grizzly bear food items, either starting with a significant trade off or small trade off, were able to reach the maximum NPV. Managers could obtain maximum net present value by dropping 5% of the starting value from all grizzly bear grouped food items. This effect could be explained with the occurrence of the GBFR while there was no harvesting (Figure 3.8). There was small changes on the predicted occurrence of grouped grizzly bear food items over the planning horizon.

Predicted occurrence of individual food items had a different trend when there was no harvesting (Figure 3.9). The value of the predicted occurrence of buffaloberry, sweet vetch, and anting did not change much with no harvesting. However, the predicted occurrence of cow-parsnip and ungulate carcass increased until the thirteenth planning horizon interval, then their occurrences decreased. The occurrences of huckleberry and clover decreased until the thirteenth planning horizon interval. Then huckleberry started increasing gradually, while clover demonstrated an irregular trend. The trend of occurrences of individual grizzly bear food items change after thirteenth planing interval because of the lifespan restriction of forested land covers. I set 250 years as maximum age any forested land cover type may reach. That is why forest gets younger after the thirteenth time interval, even though there was no harvesting.



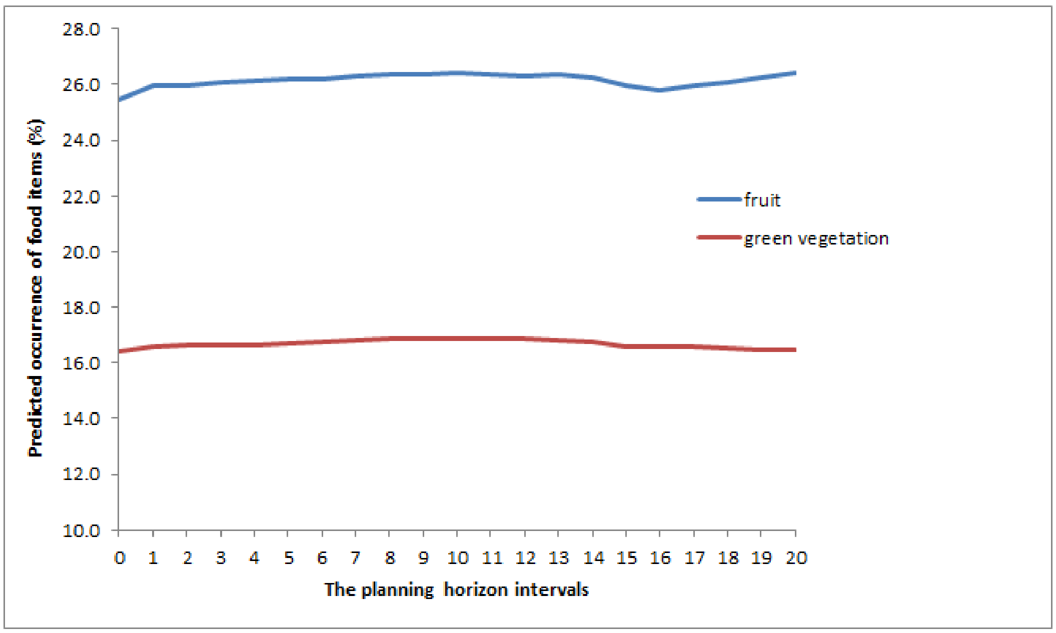


Figure 3.8: Predicted occurrence of grizzly bear grouped food items with no harvesting over the planning horizon for the study area.

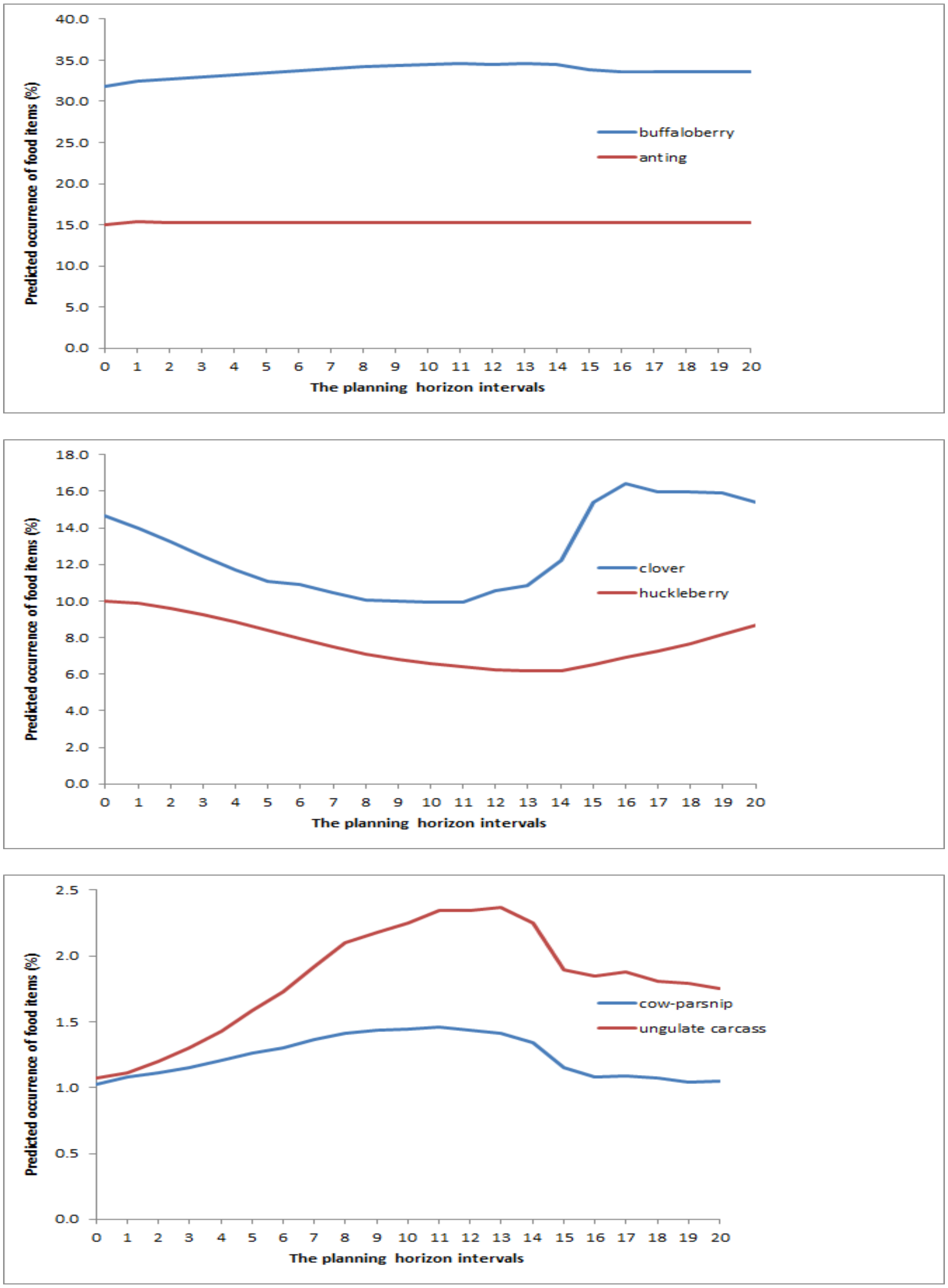


Figure 3.9: Predicted occurrence of grizzly bear individual food items with no harvesting over planning horizon in the study area.

3.4 Conclusion

Neither maximizing forest volume, nor maximizing net present value had a large negative effect on the occurrence of grizzly bear food resources. Moreover, harvesting had a positive effect on some of the grizzly bear food items. I ran six different optimization models to find management regimes to protect grizzly bear food items while maximize harvesting. Two different objective functions were used for models: maximize harvesting volume and maximize net present value. Maximizing harvesting volume was used because of the Alberta Government volume-based harvesting policy. Maximizing the net present value objective function was employed because it is a better representation of the value of the forest for timber production. On the other hand, grizzly bear food items were used individually and as a group, because grouped food items might give the better representation of their trade-off. The findings of this study show that the net present value might represent a reasonable direction in which current policy may evolve. Also, grouped grizzly bear food items had smaller trade-offs with NPV and volume than individual food items. It might be better to consider these grouped food items for management plans.

Nielsen et al. (2008) concluded that natural disturbance-based forestry or the size of disturbances had small effect on the declining population size of grizzly bear and habitat quality. The findings of this study support that view. Changing vegetation cover, which comes with harvesting, does not negatively affect grizzly bear food resources and habitat; however, forest harvesting activities increase human-caused bear mortalities (Nielsen et al., 2004b). Grizzly bears select near roads habitats and road-like habitats (Ciarniello et al., 2007; Roever et al., 2008), and forest harvesting activities requires various road construction. Road constructions give an access for hunters, poachers, vehicles, and these are the major reason major reasons for human-caused bear mortalities (McLellan, 1989).

Focusing on vegetation changes to conserve the grizzly bear population is not particularly important, especially for this study area. Other resource extraction activities, such as oil and gas, and frequency of roads or road construction near the grizzly bear home range should be considered for future research. The result could be used by land managers who seek to find the efficient combination of timber revenue and availability of grizzly bear food resources.

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Chapter 4

Discussion and conclusions

This thesis presented two studies related to the optimization of forest harvesting and grizzly bear population in west-central Alberta. In the first study (Chapter 2), disturbances of grizzly bear food items were modeled for 20×20 m area depending on environmental characteristics of 30×30 m pixels of the study area. The environmental characteristics shaping the models were age, land cover, land cover-age interaction, elevation, slope and aspect. All variables had a significant effect on the occurrence of the grizzly bear habitat at different levels, especially the effect of land cover types and elevation that were more obvious and dominant than other variables. The distribution of grizzly bear habitat was also predicted by Nielsen et al. (2010); however, the magnitude of differences between this study and Nielsen et al. (2010) includes environmental characteristics used to predict models, more specifically forested land cover-age interaction variables. Land cover-age interaction variables had a significant effect on the occurrence of grizzly bear food items at different levels and directions than the individual effects of land cover and age variables. These interactions improve models better fit with age also driving management plans that aim to sustain grizzly bear habitat and timber harvest.

The second study presented in this thesis (Chapter 3) determined the impact of forest management regimes on the occurrence of the grizzly bear habitat using a linear programming optimization technique. More specifically, trade-offs between timber harvest and the production of various food resources for grizzly bears were examined with six different management models. Models maximized either timber volume or net present value of timber harvest while maintaining specified amounts of individual grizzly bear food items or group food items. The results of the models showed that either maximum harvesting volume or maximum harvesting value can be obtained while still retaining 90% of the grizzly bear food resources. Changing vegetation cover that comes with harvesting does not seem to have a large negative effect on the occurrence of grizzly bear food items. Harvesting can positively effect on the occurrence of grizzly bear food items such as clover and huckleberry.

Considering the negligible effect of changing vegetation cover on the grizzly bear habitat, decreasing the timber harvest level to protect the grizzly bear population does not seem to be important for this study area. However; forest harvesting provides a risk for increased human-caused bear mortalities (Nielsen et al., 2004), which represents a large portion of the bear mortalities (Benn and Herrero, 2002; Gailus, 2013). Also, increasing a road network associated with harvesting provides access for hunters, poachers and vehicles (McLellan, 1989; Alberta Grizzly Bear Recovery Plan 2008-2013, 2008). It would be worthwhile for future studies to calculate human access and road network into the management plans to protect grizzly bear population.

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Appendices

Appendix A

Probability of occurrence for selected grizzly bear food items

The graphs below show predicted occurrence of eight (8) grizzly bear food items in forested land-age and unforested land-elevation environmental gradients used for describing food occurrences based on the logistic regression models developed in Chapter 2. For example, occurrences of ungulate carcass in dense conifer forest increase 0.05% with respect to age changes every 10 years, occurrences of buffaloberry increased 0.1% with respect to elevation changes in unforested areas. For both individual gradients, remaining environmental factors included in the model were held at their mean level.

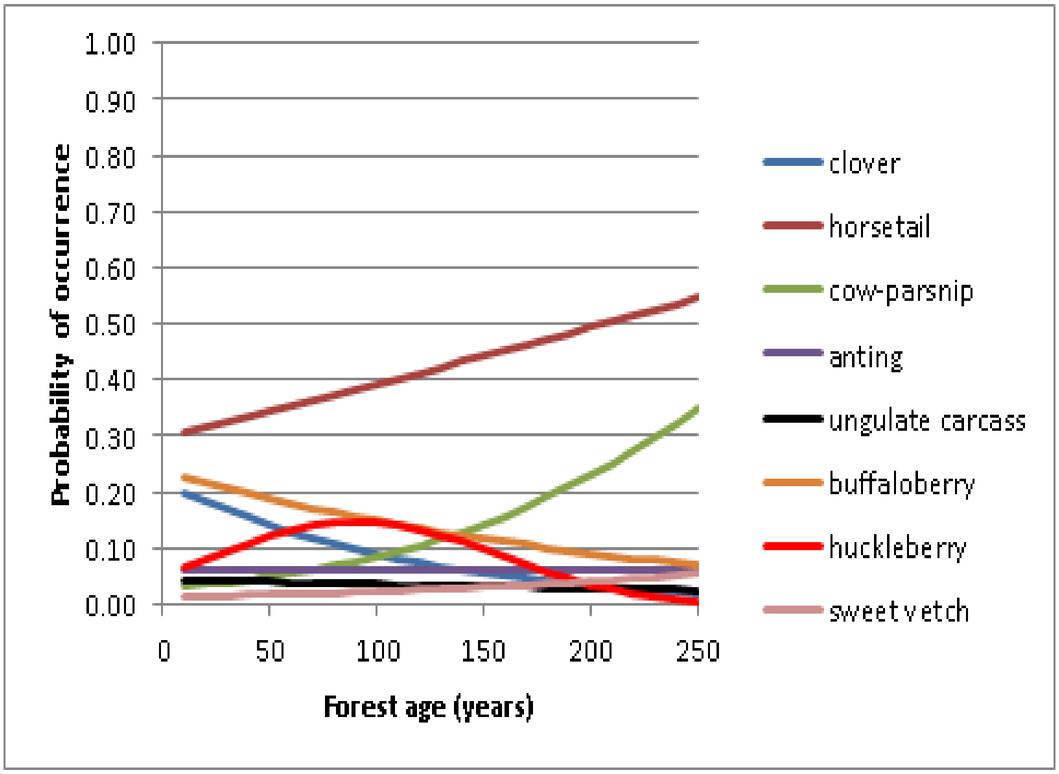

Figure A.1: Predicted probability of occurrence for eight of grizzly bear food resources in age under dense conifer forest.

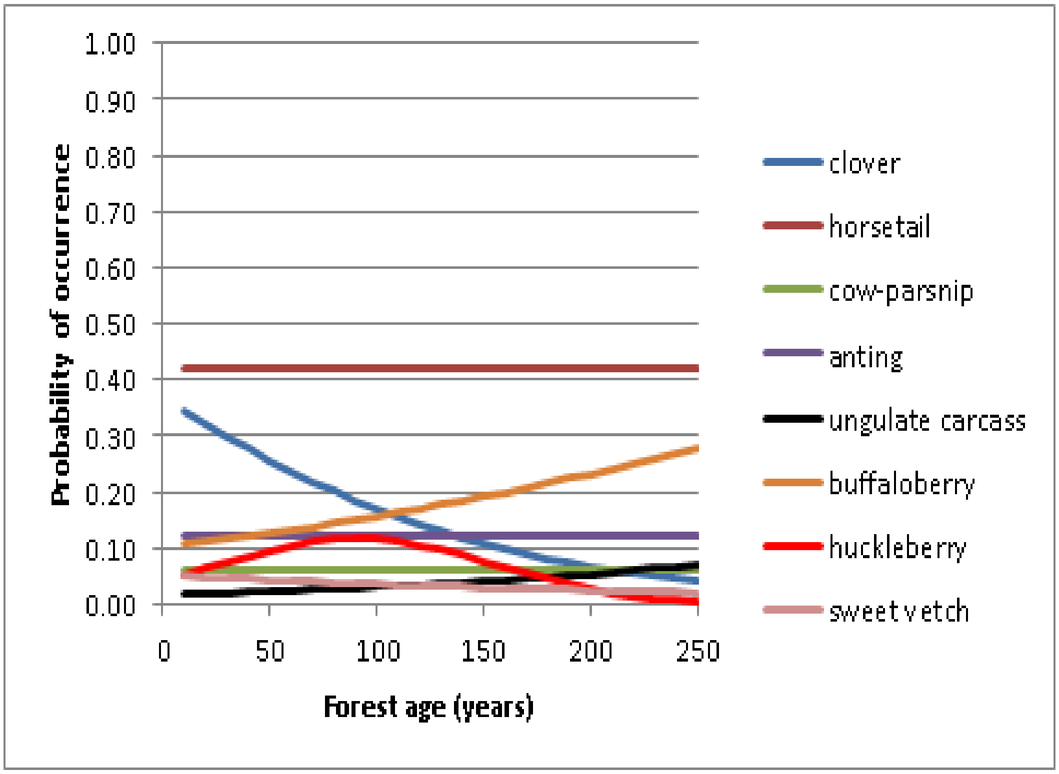

Figure A.2: Predicted probability of occurrence for eight of grizzly bear food resources in age under moderate conifer forest.

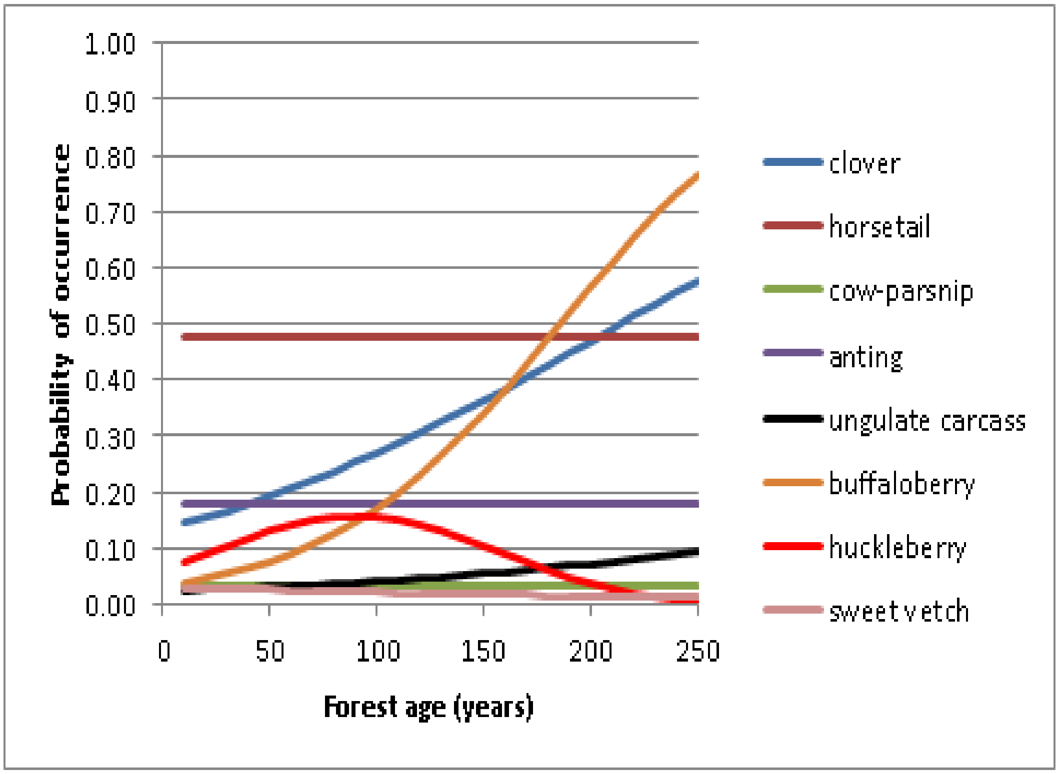

Figure A.3: Predicted probability of occurrence for eight of grizzly bear food resources in age under open conifer forest.

Figure A.4: Predicted probability of occurrence for eight of grizzly bear food resources in age under mixed forest.

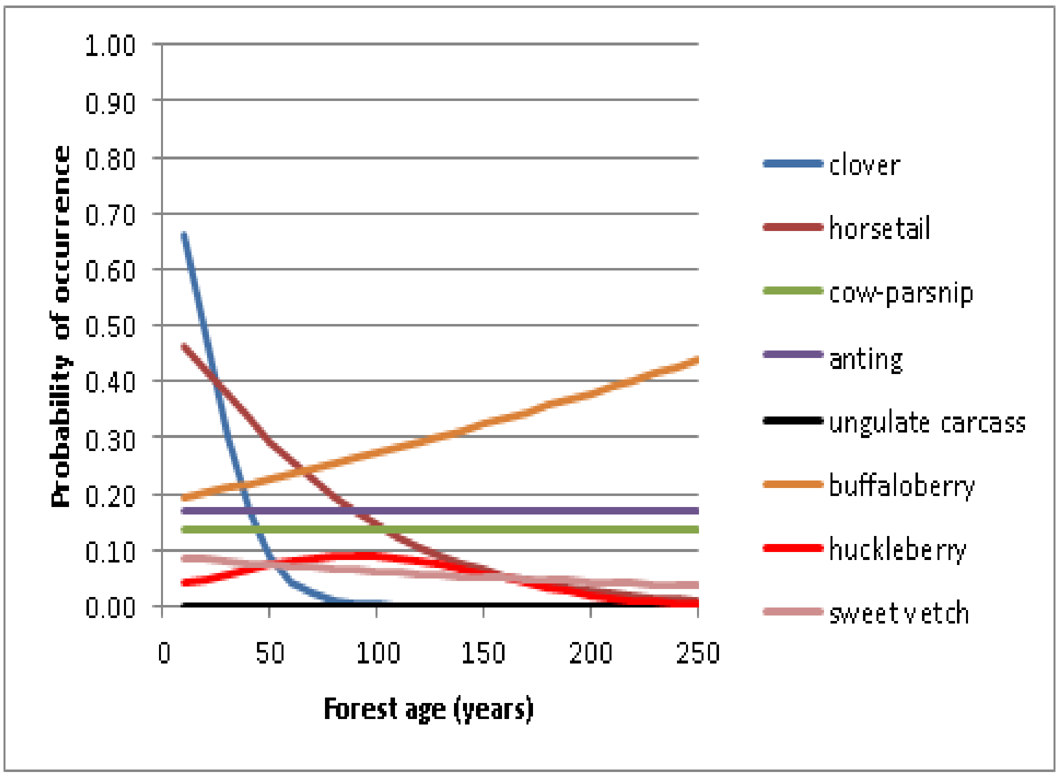

Figure A.5: Predicted probability of occurrence for eight of grizzly bear food resources in age under broadleaf forest.

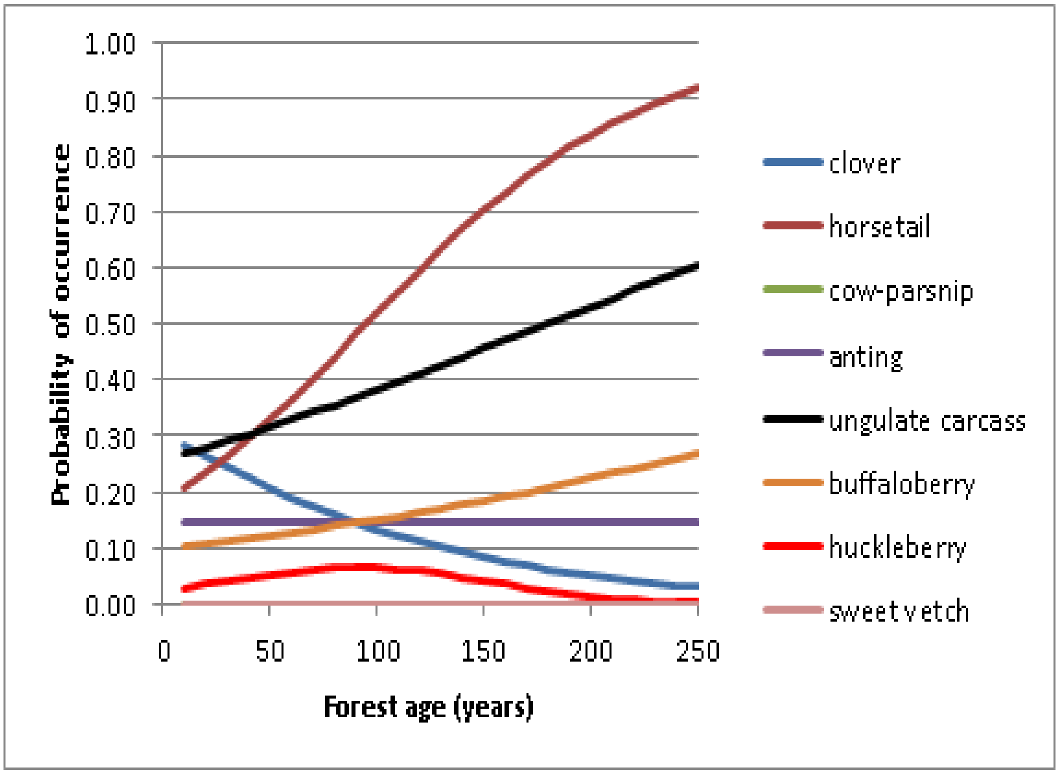

Figure A.6: Predicted probability of occurrence for eight of grizzly bear food resources in age under open wetland.

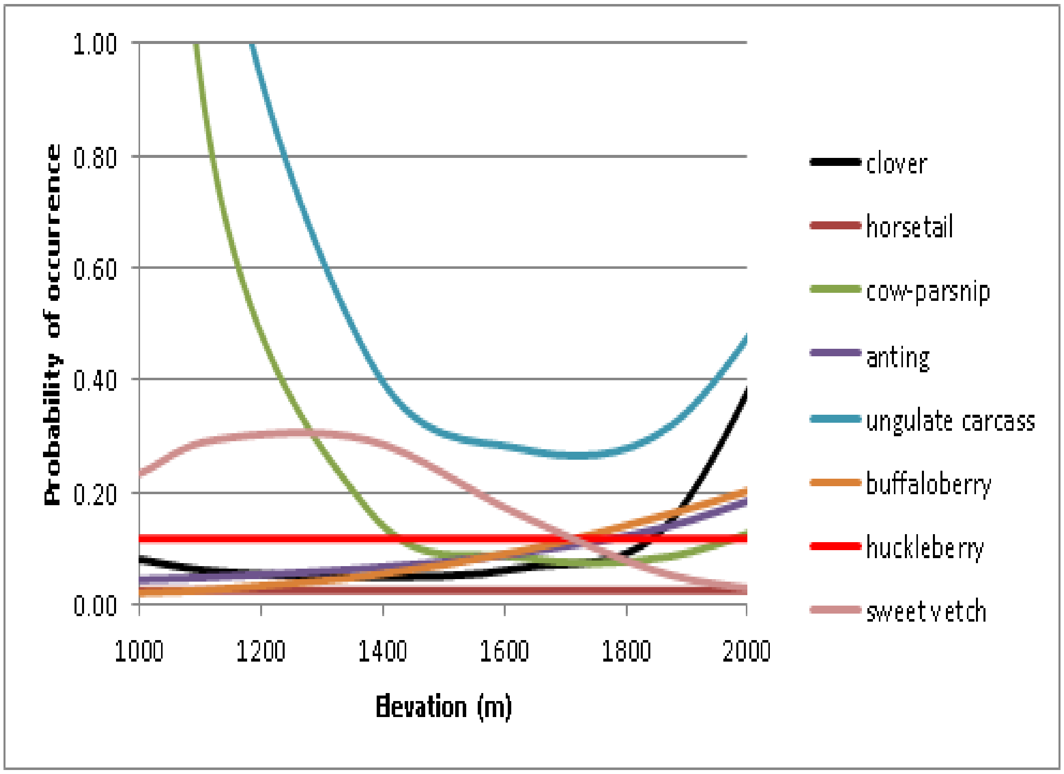

Figure A.7: Predicted probability of occurrence for eight of grizzly bear food resources in elevation.

Appendix B

Woodstock model formulation

Constants section

Fixed variable used in the models are included in this section.

```
woodprice: 50          ; $/m^3 woodprice at the mill
hcostha: 2500          ; $/ha fixed logging and log haul cost
hcostm3: 15            ; $/m^3 variable cost
regencostcon: 800      ;$/m^3 regeneration cost for conifer species
regencostot: 0         ;$/m^3 regeneration cost for other species
lower: 1.00            ;number for deciding the % value of GBFR
drate: 5%              ;discount rate
```

Landscape section

This section is where the combination of themes are defined, which lead to development types. Themes are used to describe characteristics of forest.

```
*THEME landcover {1}
DC ;Dense conifer
MC ;Moderate conifer
OC ;Open conifer
MF ;Mixed forest
BF ;Broadleaf forest
```

```
TW ;Treed wetland
OW ;Open wetland
Sh ;Shrubs
Herb ;Herbaceous
BL ;Barren land (cutblocks)
Water ;Water
Snw/I ;Snow/Ice
;Cloud ;Cloud/NoData
;Shadow ;Shadow/NoData
Rock ;Rocks

*AGGREGATE forested
DC MC OC MF BF

*AGGREGATE unforested
TW OW Sh Herb BL Water Snw/I Rock

*AGGREGATE con
DC MC OC

*AGGREGATE mixed
MF

*AGGREGATE deci
BF

*AGGREGATE ot
MF BF

*THEME elevation {2}
1000 ; <=1000
1125 ; 1001 - 1250
1375 ; 1251 - 1500
1625 ; 1501 - 1750
1875 ; 1751 - 2000
2125 ; 2001 - 2250
2375 ; 2251 - 2500
2501 ; >=2501
```

```
*THEME aspect {3}
N  ; <=45 - >=315 mid. point=0
E  ; 46 - 135     mid. point=90
S  ; 136 - 225    mid. point=180
W  ; 226 - 315    mid. point=270

*THEME slope {4}
8   ; 0 - 15
23  ; 16 - 30
38  ; 31 - 45
46  ; >=46

*THEME mangementtype {5}
existing
lfn
xx

*THEME fromtype{6}
DC ;Dense conifer
MC ;Moderate conifer
OC ;Open conifer
MF ;Mixed forest
BF ;Broadleaf forest
TW ;Treed wetland
OW ;Open wetland
Sh ;Shrubs
Herb ;Herbaceous
BL ;Barren land(cutblocks)
Water ;Water
Snw/I ;Snow/Ice
Rock ;Rocks

*AGGREGATE forested
DC MC OC MF BF

*AGGREGATE unforested
TW OW Sh Herb BL Water Snw/I Rock

*AGGREGATE con
```

```
DC MC OC

*AGGREGATE mixed
MF

*AGGREGATE deci
BF

*THEME {7}
xx

*THEME {8}
xx

*THEME {9}
xx

*THEME {10}
xx
```

Lifespan section

Lifespan section is used to indicate maximum age a development type may reach before to die or be replaced by another development types. All of the unforested development types were set to 1, and forested development types were set to 26.

```
Sh ? ? ? ? ? ? ? ? ? ? 1
Herb ? ? ? ? ? ? ? ? ? 1
BL ? ? ? ? ? ? ? ? ? ? 1
Water ? ? ? ? ? ? ? ? ? 1
Snw/I ? ? ? ? ? ? ? ? ? 1
Rock ? ? ? ? ? ? ? ? ? 1
? ? ? ? ? ? ? ? ? ? 26
```

Areas section

Area section is used to indicate area of development types in different age class at the beginning of the planning period.

```
*A    BF 1000 E 8 EXISTING BF xx xx xx xx  1  14.22
...<% (978 lines are omitted)
```

Yields section

Yield section is used to provide growth information of the forest, such as yield tables. Age dependent yield tables of forested development types show soft wood volume, hard wood volume, total volume and height of the stand. Yield tables of GBFR show predicted probability of occurrence of food resources under different development types. Yield tables of GBFR estimated from regression models obtained in Chapter 2 and wrote out with the code in ERA. This section also includes the time dependent yields based on the discount factor. Discount factor is generated based on the discount rate for a 10 years planning period in the middle point of the planning period.

```
*Y DC ? ? ? existing ? ? ? ? ?
_AGE ySvol yHvol ytvol yht
 2   7.6  1.0   8.6  3.6
 3  37.1  2.0  39.1  6.6
 4  68.9  4.0  72.9  9.3
 5 116.5  5.7 122.3 11.7
 6 156.8  7.0 163.8 13.8
 7 186.4  8.5 194.9 15.5
 8 203.1 11.0 214.1 17.0
 9 217.8 12.3 230.1 18.3
10 229.9 13.3 243.2 19.3
11 240.6 14.2 254.9 20.2
12 249.2 15.1 264.3 21.0
13 254.0 17.1 271.1 21.7
14 257.9 18.9 276.8 22.3
15 261.1 20.5 281.6 22.8
16 263.9 21.9 285.8 23.3
17 266.4 23.2 289.5 23.7
18 268.7 24.3 293.0 24.1
19 271.0 25.3 296.3 24.4
20 273.1 26.2 299.3 24.7
```

```
21 275.0 27.0 302.0 25.0
22 276.5 27.7 304.2 25.2
23 277.8 28.4 306.3 25.5
24 279.1 29.0 308.1 25.7
25 280.2 29.6 309.8 25.9
26 281.3 30.1 311.4 26.0
27 282.4 30.6 313.0 26.2
28 283.4 31.0 314.5 26.3
29 284.4 31.5 315.8 26.5
30 285.3 31.8 317.1 26.6
31 286.1 32.2 318.3 26.7
32 286.9 32.5 319.4 26.8
33 287.6 32.8 320.4 26.9
34 287.6 33.2 320.7 27.0
35 286.6 33.5 320.1 27.1
36 285.6 33.9 319.5 27.2
37 284.8 34.2 318.9 27.3
38 283.9 34.5 318.4 27.4
39 283.1 34.8 317.9 27.4
40 282.4 35.0 317.4 27.5
41 281.7 35.3 317.0 27.6
42 281.0 35.5 316.6 27.6
...<% (222 lines are omitted)

*Y DC 1000 N 8  existing ? ? ? ? ?
_AGE clover equisetum hela anting ungulate_k hedy shca vame
1 0.1415876 0.3499599 0.001209296 0.08425881 0.003326075 0.03826932 0.4540957
2 0.1292967 0.3595129 0.001359436 0.08425881 0.003247543 0.04107567 0.4401971
3 0.1179262 0.3691785 0.001528187 0.08425881 0.003170859 0.04407838 0.4263917
4 0.1074323 0.3789503 0.00171785 0.08425881 0.003095981 0.04728978 0.4127
5 0.09776861 0.3888212 0.001931006 0.08425881 0.003022865 0.05072273 0.399142
6 0.08888766 0.3987842 0.002170554 0.08425881 0.00295147 0.05439067 0.3857369
7 0.08074123 0.4088318 0.002439747 0.08425881 0.002881757 0.05830755 0.3725029
8 0.07328136 0.418956 0.002742232 0.08425881 0.002813686 0.06248786 0.3594572
9 0.0664609 0.429149 0.003082105 0.08425881 0.002747219 0.06694658 0.3466161
10 0.06023397 0.4394024 0.003463955 0.08425881 0.002682317 0.0716991 0.3339945
11 0.05455636 0.4497078 0.003892929 0.08425881 0.002618945 0.07676125 0.3216062
12 0.0493858 0.4600566 0.004374794 0.08425881 0.002557066 0.08214917 0.309464
13 0.04468212 0.4704399 0.004916009 0.08425881 0.002496646 0.08787928 0.2975791
```

```
14 0.04040739 0.4808489 0.005523808 0.08425881 0.002437649 0.09396816 0.2859616
15 0.03652598 0.4912745 0.006206284 0.08425881 0.002380044 0.1004325 0.2746203
16 0.03300459 0.5017077 0.00697249 0.08425881 0.002323796 0.1072888 0.2635628
17 0.02981218 0.5121394 0.007832544 0.08425881 0.002268875 0.1145536 0.2527954
18 0.02691997 0.5225606 0.008797745 0.08425881 0.002215249 0.122243 0.2423231
19 0.02430132 0.5329622 0.009880703 0.08425881 0.002162888 0.1303725 0.2321498
20 0.02193165 0.5433351 0.01109548 0.08425881 0.002111761 0.138957 0.2222784
...<% (16,874 lines are omitted)

*Y OW 1000 N 8  existing ? ? ? ? ?
_AGE clover equisetum hela anting ungulate_k hedy shca vame
1 0.11334 0.5369886 8.51135e-09 0.1188934 5.006907e-10 0.1424766 0.2511037 0.145986
...<% (19,969 lines are omitted)

*YT ? ? ? ? ? ? ? ? ? ? ?
yDfact _DISCOUNTFACTOR (#drate,10,half)
```

Actions section

This section is where the harvesting action is defined. Harvesting is clear-cut followed by natural regeneration when the total volume of the forested area is greater than or equal to 50 m^3/ha.

```
*ACTION aClrctLFN Y
*OPERABLE aClrctLFN
forested ? ? ? ? ? ? ? ? ? yTvol >= 50
```

Transitions section

Transitions section describes how development types will respond to clear-cut action over planning periods or the case of death due to the end of their lifespan.

```
*CASE aClrctLFN
*SOURCE ? ? ? ? ? ? ? ? ? ?
*TARGET bl ? ? ? ? ? ? ? ? ? 90
*TARGET sh ? ? ? ? ? ? ? ? ?  10
```

```
*TARGET ? ? ? ? ? ? ? ? ? ?  0

 *CASE _DEATH
*SOURCE Water ? ? ? ? ? ? ? ? ? ?
*TARGET ? ? ? ? ? ? ? ? ? ?  100
...<% (46 lines are omitted)
```

Outputs section

This section is used to control outputs which are important to report.
Objective function and constraints are established as an output in this section.

```
*OUTPUT otvol         ;total volume harvested
*SOURCE aClrctLFN ytvol

*OUTPUT ohvol         ;hardwood volume harvested
*SOURCE aClrctLFN yhvol

*OUTPUT osvol         ;softwood volume harvested
*SOURCE aClrctLFN ysvol

*OUTPUT oshca        ;total value of shca on the study area
*SOURCE _INVENT shca

*OUTPUT oclover      ;total value of clover on the study area
*SOURCE _INVENT clover

*OUTPUT oequisetum   ;total value of equisetum on the study area
*SOURCE _INVENT equisetum

*OUTPUT oAreaCut     ;Area  cut
*SOURCE aClrctLFN _AREA

*OUTPUT oHarvRev     ;harvest revenue
*SOURCE oTvol * #woodprice

*OUTPUT oHarvCost    ;harvesting cost
*SOURCE oAreaCut * #hcostha + oTvol * #hcostm3
```

```
*OUTPUT oRegenCost    ;regeneration cost
*SOURCE oareacutcon * #regencostcon + oareacutot * #regencostot

*OUTPUT oDiscRev      ;discounted revenue
*SOURCE oHarvRev * yDfact

*OUTPUT oDiscCost     ;discounted cost
*SOURCE oHarvCost * yDfact + oRegenCost * yDfact
...<% (32 lines are omitted)
```

Graphics section

This section is where commands are given to shift out graphical outputs.

```
*PAGE
*PALETTE _Default
*SCREENSIZE MAXIMIZED
*FONT1 "Tahoma" 8 0 0000
*FONT2 "Tahoma" 8 0 0000
*FONT3 "Tahoma" 8 0 0000
*WINDOW {1}(2,0,495,334) ""
  _LEGEND (438,29)
_YAXIS(*,*,1,*)
*WINDOW {2}(0,333,499,666) ""
  _LEGEND (414,355)
_YAXIS(*,*,*,*)
...<% (103 lines are omitted)
```

Optimize section

Optimize section is where the models are formulated as a LP model. Objective function and constraints are shown in this section. Even flow constraint is used to control how much hardwood or softwood come out of the land. Other constraints are used to track how much food items are on the land.

```
*OBJECTIVE
;_MAX otvol 1.._LENGTH
;_MAX oDiscRev - oDiscCost 1.._LENGTH

*CONSTRAINTS
;otvol = 0 1.._LENGTH    ;no harvesting
;_EVEN(otvol) 1.._LENGTH                         ;
;oanting - #lower * oanting[0] >= 0 1.._LENGTH
;oshca - #lower * oshca[0] >= 0 1.._LENGTH
;oequisetum - #lower * oequisetum[0] >= 0 1.._LENGTH
;oclover - #lower * oclover[0] >= 0 1.._LENGTH
;ohela - #lower * ohela[0] >= 0 1.._LENGTH
;ohedy - #lower * ohedy[0] >= 0 1.._LENGTH
;oungulate_k - #lower * oungulate_k[0] >= 0 1.._LENGTH
;ovame - #lower * ovame[0] >= 0 1.._LENGTH
;ogreen_veg - #lower * ogreen_veg[0] >= 0 1.._LENGTH
;ofruit - #lower * ofruit[0] >= 0 1.._LENGTH
;oroot - #lower * oroot[0] >= 0 1.._LENGTH
;oanimal_m - #lower * oanimal_m[0] >= 0 1.._LENGTH

*FORMAT MOSEK
```

Schedule section

This section is where the optimal management schedule is shown. It is created by Woodstock LP solver. Management schedule shows the actions performed by LP solver on development types associated with age class and area over planning horizon.

```
BF 1125 E 8 existing BF xx xx xx xx 26 0.63 _DEATH 1 _EXISTING
BL 1000 E 8 existing BL xx xx xx xx 1 34.83 _DEATH 1 _EXISTING
BL 1000 E 8 existing DC xx xx xx xx 1 34.83 _DEATH 1 _EXISTING
BL 1000 E 8 existing MC xx xx xx xx 1 34.83 _DEATH 1 _EXISTING
BL 1000 N 8 existing BL xx xx xx xx 1 6.54 _DEATH 1 _EXISTING
BL 1000 N 8 existing DC xx xx xx xx 1 6.54 _DEATH 1 _EXISTING
BL 1000 N 8 existing MC xx xx xx xx 1 6.54 _DEATH 1 _EXISTING
BL 1125 E 23 existing BL xx xx xx xx 1 183.6 _DEATH 1 _EXISTING
BL 1125 E 23 existing DC xx xx xx xx 1 183.6 _DEATH 1 _EXISTING
```

```
BL 1125 E 23 existing MC xx xx xx xx 1 183.6 _DEATH 1 _EXISTING
...<% (1642 lines are omitted)
```

Appendix C

Woodstock models results

Table C.1: The periodic harvest volume (m^3) per decade and the NPV ($) for individual food resources. The model maximizing volume while keeping the specified proportion of the initial value of GBFR. Proportion of GBFR varies between 100% and 75%.

GBFR		Volume (m^3) / NPV ($) according to specified amount of the GBFR					
		1.00	0.95	0.90	0.85	0.80	0.75
anting	(m^3)	1.14×10^7	1.20×10^7	–	–	–	–
	($)	5.30×10^8	5.40×10^8	–	–	–	–
buffaloberry	(m^3)	1.12×10^7	1.19×10^7	1.20×10^7	–	–	–
	($)	5.13×10^8	5.31×10^8	5.40×10^8	–	–	–
clover	(m^3)	1.20×10^7	–	–	–	–	–
	($)	5.45×10^8	–	–	–	–	–
cow-parsnip	(m^3)	1.04×10^7	1.08×10^7	1.12×10^7	1.15×10^7	1.18×10^7	1.20×10^7
	($)	4.64×10^8	4.84×10^8	4.99×10^8	5.11×10^8	5.24×10^8	5.37×10^8
horsetail	(m^3)	8.84×10^6	1.13×10^7	1.20×10^7	–	–	–
	($)	3.98×10^8	5.00×10^8	5.38×10^8	–	–	–
huckleberry	(m^3)	Inf.	1.14×10^7	1.18×10^7	1.20×10^7	–	–
	($)	Inf.	5.09×10^8	5.29×10^8	5.36×10^8	–	–
sweet vetch	(m^3)	1.02×10^7	1.20×10^7	–	–	–	–
	($)	4.39×10^8	5.42×10^8	–	–	–	–

Continued on next page

Table C.1 – continued from previous page

GBFR		Volume (m^3) / NPV($) according to specified amount of the GBFR					
		1.00	0.95	0.90	0.85	0.80	0.75
ungulate	(m^3)	1.20×10^7	–	–	–	–	–
carcass	($)	5.38×10^8	–	–	–	–	–
all of GBFR	(m^3)	Inf	1.00×10^7	1.09×10^7	1.14×10^7	1.18×10^7	1.20×10^7
included	($)	Inf	4.55×10^8	4.82×10^8	5.06×10^8	5.24×10^8	5.37×10^8
none of GBFR	(m^3)	1.20×10^7					
included	($)	5.37×10^8					

Inf = the solution was infeasible.

- = model not run. Volume reached its maximum, it is therefore unnecessary to run.

(m^3) value calculated per decade, ($) value calculated for planning horizon.

Table C.2: The periodic harvesting volume (m^3) per decade and the NPV (\$) for grouped food resources. The model maximizes harvest volume while keeping the specified proportion of the initial value of grizzly bear food resource groups. Proportion varies between 100% and 75%.

GBFR		Volume (m^3) / NPV (\$) according to specified amount of the GBFR					
		1.00	0.95	0.90	0.85	0.80	0.75
Animal	(m^3)	1.19×10^7	1.20×10^7	–	–	–	–
matter	(\$)	5.27×10^8	5.39×10^8	–	–	–	–
Fruit	(m^3)	1.09×10^7	1.18×10^7	1.20×10^7	–	–	–
	(\$)	5.01×10^8	5.27×10^8	5.44×10^8	–	–	–
Green	(m^3)	1.12×10^7	1.20×10^7	–	–	–	–
vegetation	(\$)	4.99×10^8	5.41×10^8	–	–	–	–
Root	(m^3)	1.02×10^7	1.20×10^7	–	–	–	–
	(\$)	4.39×10^8	5.42×10^8	–	–	–	–

- = model not run. Volume reached its maximum, it is therefore unnecessary to run.

(m^3) value calculated per decade, (\$) value calculated for planning horizon.

Table C.3: The periodic harvesting volume (m^3) per decade and the NPV (\$) for individual food resources. The model maximizes net present value while keeping the specified proportion of the initial value of GBFR. Proportion of GBFR varies between 100% and 75%.

GBFR		Volume (m^3) / NPV (\$) according to specified amount of the GBFR					
		1.00	0.95	0.90	0.85	0.80	0.75
anting	(m^3)	1.15×10^7	1.19×10^7	1.19×10^7	–	–	–
	(\$)	5.38×10^8	5.62×10^8	5.65×10^8	–	–	–
buffaloberry	(m^3)	1.12×10^7	1.18×10^7	1.19×10^7	–	–	–
	(\$)	5.27×10^8	5.59×10^8	5.65×10^8	–	–	–
clover	(m^3)	1.19×10^7	–	–	–	–	–
	(\$)	5.65×10^8		–	–	–	–
cow-parsnip	(m^3)	1.03×10^7	1.07×10^7	1.10×10^7	1.14×10^7	1.17×10^7	1.19×10^7
	(\$)	4.80×10^8	5.05×10^8	5.23×10^8	5.39×10^8	5.53×10^8	5.65×10^8
horsetail	(m^3)	8.69×10^6	1.12×10^7	1.19×10^7	–	–	–
	(\$)	4.17×10^8	5.32×10^8	5.65×10^8	–	–	–
huckleberry	(m^3)	Inf	1.14×10^7	1.17×10^7	1.19×10^7	1.19×10^7	–
	(\$)	Inf	5.36×10^8	5.55×10^8	5.62×10^8	5.65×10^8	–
sweet vetch	(m^3)	1.02×10^7	1.19×10^7	1.19×10^7	–	–	–
	(\$)	4.59×10^8	5.63×10^8	5.65×10^8	–	–	–

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Table C.3 – continued from previous page

GBFR		Volume (m^3) / NPV($) according to specified amount of the GBFR					
		1.00	0.95	0.90	0.85	0.80	0.75
ungulate	(m^3)	1.12×10^7	1.19×10^7	–	–	–	–
carcass	($)	5.63×10^8	5.65×10^8	–	–	–	–
all of GBFR	(m^3)	Inf	9.90×10^6	1.08×10^7	1.13×10^7	1.17×10^7	1.19×10^7
included	($)	Inf	4.68×10^8	5.11×10^8	5.36×10^8	5.53×10^8	5.65×10^8
none of GBFR	(m^3)	1.19×10^7					
included	($)	5.65×10^8					

Inf = the solution was infeasible.

- = model not run. Net present value reached its maximum, so it is unnecessary to run.

(m^3) value calculated per decade, ($) value calculated for planning horizon.

Table C.4: The periodic harvesting volume (m^3) per decade and the NPV ($) for grouped food resources. The model maximizes net present value while keeping the specified proportion of the initial value of grizzly bear food resource groups. Proportion varies between 100% and 75%.

GBFR		Volume (m^3) / NPV ($) according to specified amount of the GBFR					
		1.00	0.95	0.90	0.85	0.80	0.75
Animal	(m^3)	1.18×10^7	1.19×10^7	1.19×10^7	–	–	–
matter	($)	5.57×10^8	5.64×10^8	5.65×10^8	–	–	–
Fruit	(m^3)	1.09×10^7	1.17×10^7	1.19×10^7	–	–	–
	($)	5.13×10^8	5.55×10^8	5.65×10^8	–	–	–
Green	(m^3)	1.11×10^7	1.19×10^7	–	–	–	–
vegetation	($)	5.20×10^8	5.65×10^8	–	–	–	–
Root	(m^3)	1.02×10^7	1.19×10^7	1.19×10^7	–	–	–
	($)	4.59×10^8	5.63×10^8	5.65×10^8	–	–	–

- = model not run. Net present value reached its maximum, so it is unnecessary to run.
(m^3) value calculated per decade, ($) value calculated for planning horizon.