CONTROLLING THE INVASION OF SERICEA LESPEDEZA (*LESPEDEZA CUNEATA*) WITH LIMITED BUDGETS: INSIGHTS FROM AN OPTIMIZATION MODEL

A Thesis by

Rajesh Kumar Narasimhan

Bachelor of Engineering, Anna University, India, 2008

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Industrial and Manufacturing Engineering.

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Esra Büyüktahtakın, Committee Chair

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Krishna K. Krishnan, Committee Member

____
Gregory R. Houseman, Committee Member

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ABSTRACT

Sericea Lespedeza *(Lespedeza cuneata)*, a perennial legume native to Asia, has been introduced in the United States for erosion control, providing forage to livestock and wildlife cover. It is drought tolerant, can grow in a range of soil types, and produces enormous amounts of seeds, which result in the establishment of the Sericea Lespedeza population very quickly. Native grasslands in the Great Plains are threatened by the spread of Sericea Lespedeza, which can damage forage or hay production leading to substantial economic costs to landowners. Sericea Lespedeza has been declared as a noxious weed by the state of Kansas.

The current practice for controlling the growth of Sericea Lespedeza is by using herbicides. Although they are available, effective control can be expensive because of the scale of the problem and the necessity of repeated herbicide applications over many years to kill the new plants germinating from the long-lived seed bank. In this thesis, a dynamic nonlinear 0-1 integer programming model is developed to find economically efficient strategies to control the invasion of Sericea Lespedeza. Using empirical data, the model considers population growth rates, carrying capacity, seed dispersal, treatment costs, and economic loss due to invasion. The model minimizes the sum of damages to hay and forage due to the invasion of Sericea Lespedeza over time subject to two constraints: (1) the spread of invasive species over space and time, and (2) budget restricting the total cost of labor and herbicides used to prevent and control these invasive species. Finally, this thesis present results from different management scenarios as well as using various parameters considered in the model such as budget, dispersal rates, kill rates of the herbicides and initial infestation to provide insights regarding economically efficient strategies for controlling Sericea Lespedeza in the Great Plains.

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CHAPTER 1

INTRODUCTION

1.1 Process of Biological Invasion

Biological invasion occurs when an organism establishes a sustaining population in a new range by competing with the native species. Invasion is a natural process but one that has accelerated over the past several centuries due to accidental and intentional introduction by humans. The invasion of biological species has increased the attention of many ecologists and scientists after Elton (1958) proposed the invasive species as a potential global threat. Invasions have been an important component of the evolutionary process throughout geological history. The main reason for studying invasions is that many invasive species have become serious pests.

Jonathan (2009) studied biological invasions by examining the controls over different stages of the invasion process. Biological invasions begin as introductions with trade and travel or as international introductions that spread outside their intended use. Establishment of invasive species is the process by which the population of an introduced species increases. The ability of an invasive species to establish depends on habitat suitability and competitive effects from other established species. Although some species establish, the rate of spread across the landscape can vary substantially among species. Dispersal of propagules contributes to the spread of invasive species. Biological invasion poses a threat to the native ecosystems through competition, predation, and invaders. In particular, invaders can have strong negative effects on the abundance of native species.

Sericea Lespedeza a perennial legume, was introduced into the United States by the U.S. Department of Agriculture (USDA) in 1900 for erosion control, wildlife cover, and forage. It is recognized for its tolerance of drought, acidity, and shallow soils of low fertility. Sericea

Lespedeza is a prolific seed producer. According to Ohlenbusch et al. (2007), Sericea Lespedeza is the first federally listed forage crop that was declared a noxious weed. It is predominantly found across eastern counties in Kansas (Kansas Department of Agriculture, 2010). However, it has spread westward through the Conservation Reserve Program (CRP). It was first recognized as a potential threat in southeast Kansas in the early 1980s. Since that time, Sericea Lespedeza has spread throughout Kansas.

1.2 Economical and Ecological Impact of Invasive Species

The introduction of invasive species results in economic and ecological damage. Economic impact is classified as either direct or indirect cost. Preventive measures such as chemical (herbicides), mechanical, and biological control methods are considered a direct cost. The damage caused by invasive species such as loss in revenue from the native species is considered an indirect cost (Global Invasive Species Program, 2008).

The introduction of invasive species affects the growth of native species, while their establishment affects an ecosystem's biodiversity. Chornesky et al. (2003) proposed that native species are driven to extinction by invasive species through predation, parasitism, disease, and competition among other species. According to Cleeland and Mooney (2001), hybrid species are formed by the process of mating between invasive and native species, which can potentially displace the native species, thus leading to the loss of stability among the growth of the native population and eventual extinction.

According to D'Antonio and Dudley (1996), the invasion of invasive species is growing as a global threat, increasing health problems, reducing the value of agricultural products, and costing U.S. taxpayers billions of dollars annually in environmental degradation. Pimentel et al. (2005) reported that the annual economic cost due to invasive species exceeded $120 billion in total and about $1,100 per household per year. Invasive species are also leading to sizeable environmental damage. Considering both economic and ecological factors, the net costs to destroy invasive species would be higher than $120 billion per year.

Sakai et al. (2001) performed a cost-benefit analysis of purple loosestrife for 19 eastern and north central states. As a result of this study, annual loss was estimated to be $229.3 million due to the invasion of this weed. According to Leitch et al. (1994), the economic impact of leafy spurge infestation in Montana, North Dakota, South Dakota, and Wyoming was about $130 million. The expenditures to destroy this invasive species are even more than the economic loss caused by the invasion due to inappropriate action at the right time. Invasive species grow and spread drastically due to the absence of management action.

1.3 Prevention and Control

Mechanical treatment is the most common method to control the growth of invasive species. Pulling, digging, and mowing are a few of the methods used to treat invasive species mechanically. Mechanical removal is highly labor intensive and creates a significant amount of site disturbance, which can lead to rapid reinvasion if not handled properly. It can be very difficult to eradicate the widespread of invasive species by using mechanical treatment. Chemical treatment involves using chemicals to kill invasive species. Herbicides are among the most effective and resource-efficient tools to treat invasive species. They are sprayed by different methods based on the spread of invasive species. Although chemicals can effectively control some species, chemical treatment has limitations, such as their negative effect on no-target species. Chemical treatment can be expensive and may only be effective for a short period of time. On the other hand, biological control introduces an enemy of invasive species (i.e., a parasite, predator, competitor) to reduce the population. Controlling the invasive species using a biological control method may also sometimes produce a negative impact on the native species, and it is very difficult to remove the biological treatment.

Economic and ecological damage might be reduced by preventing and controlling the growth and spread of invasive species. In particular, optimization techniques can be used to understand the spread and dispersal rate of invasive species. Neubert and Caswell (2000) performed a sensitivity analysis of the model parameters for landowners to determine where invasive species are most susceptible to control measures. Since their model provides information on the speed of invasion by considering both population growth and dispersal, landowners can control the spread of invasive species.

Koger (2002) proposed the application of herbicides to Sericea Lespedeza at different stages of their growth. Triclopyr, fluroxypyr, and metsulfuron are herbicides that are used specifically to control the growth of invasive species. Both triclopyr and fluroxypyr are applied during the branched ramet stage, and metsulfuron is applied during the flowering stage. Even though the kill rates of herbicides are high, factors such as enormous seed production and its competitive nature may influence the reestablishment of Sericea Lespedeza, which makes them ineffective for long-term control. According to Eddy and Moore (1998), the population of Sericea Lespedeza can be controlled by a biological method using Lespedeza webworms, which reduce the seed production from infested Sericea Lespedeza by 98%. However, these treatments do not provide an economical and long-term control.

1.4 Problem Statement

Sericea Lespedeza, an introduced legume from eastern Asia, is recognized as a noxious weed in Kansas. It produces a large number of seeds and has spread in various counties of Kansas. It is a serious threat to landowners since it creates economic loss in hay and forage values. Since the seeds can survive in various climatic conditions and are viable for years, the eradication of Sericea Lespedeza using suitable herbicides on a large scale is critical for long-term control. An optimization model to control the invasion of Sericea Lespedeza with a limited budget allotted to herbicide and labor is proposed. The model computes growth rate, seed dispersal, treatment costs, and economic loss due to invasion. It also minimizes the economic loss of hay and forage that is caused by Sericea Lespedeza, subject to a budget constraint. The results of this model will provide management and control strategies to landowners in dealing with Lespedeza.

1.5 Research Objective

The objective of this thesis is to present an optimization model in order to provide decision strategies to landowners for effectively controlling the damage caused by Sericea Lespedeza in Kansas. This optimization model accounts for the cost of treatments and limited resources such as a restricted budget allocated throughout the planning horizon. This thesis illustrates the influence of seed bank, longevity, population growth, spread and germination rate of seeds. A logistic growth function is used to determine the population growth of Lespedeza, where a population grows at an increasing rate at first and then stabilizes as it reaches its carrying capacity, which is the maximum possible population in a given area. The germination of Sericea Lespedeza from seed banks and the previous year's population contribute to the current year's population. The model will provide decision strategies to land managers for when and where to apply treatments to control Sericea Lespedeza with budget restrictions.

1.6 Thesis Outline

This thesis is structured into five chapters. Chapter 2 presents a literature review of previous work on the establishment and spread of invasive species, economic losses, ecological damages, and the control of the invasive species using optimization models. Chapter 3 presents a mathematical model to control the invasive species with an application to the growth and dispersal of Sericea Lespedeza in Kansas. Chapter 4 presents a case study for controlling Sericea Lespedeza, and provides background and related control techniques, as well as data collected to conduct various experiments by using the proposed mathematical modeling Chapter 3. In this chapter, A Mathematical Programming Language (AMPL) code for the model is provided, and preliminary results based on various scenarios and strategies are presented. In Chapter 5, conclusions and future research directions are discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the previous research on various mathematical models and presents a literature review of invasive species control. Section 2.2 reviews the characteristics and distribution of an invasive species named Sericea Lespedeza. Section 2.3 outlines studies on economic and environmental damages caused by invasive species. Section 2.4 discusses literature on the control of Sericea Lespedeza using herbicides. Section 2.5 presents various mathematical models used to control the growth of invasive species. Section 2.6 summarizes the literature review and presents the research motivation.

2.2 Characteristic and Distribution: Sericea Lespedeza

Sericea Lespedeza is a perennial legume native to Asia, introduced in Kansas in the year 1930. It was planted to control soil erosion, provide forage for livestock, and supply cover for wildlife. Sericea Lespedeza is a shrubby perennial about 2 to 5 feet tall with trifoliate leaves attached by petioles. It can tolerate a wide range of soil types. The root produces numerous branches and spreads laterally, which makes the weed competitive and drought resistant. Germination and environmental conditions regulate the growth of Sericea Lespedeza. The high tannin content in Sericea Lespedeza during its older stages is highly indigestible in nature resulting in poor forage quality. It inhibits the growth of other plants, thus reducing the additional cover for wildlife. Ohlenbusch et al. (2007) proposed that the production of Sericea Lespedeza seeds must be controlled by early detection and suitable treatment. The Kansas Department of Agriculture declared Sericea Lespedeza as a noxious weed and has identified a spread of the weed of around 600,000 acres across the various counties in Kansas (Kansas Department of Agriculture, 2010).

Hoveland et al. (1971) determined the establishment of Sericea Lespedeza in grassland with different seedling rates by using herbicides. An experiment was conducted by incorporating vernolate preplant with three different seeding rates. The growth of grasses and broadleaf weeds were controlled by the herbicide. At a low seeding rate, the yield of plant biomass was less. The use of herbicides reduced the seeding rate with no decrease in Sericea Lespedeza biomass. On the other hand, an increase in seeding rate increases the yield of Sericea Lespedeza. During summer, Sericea Lespedeza is in high competition with other native plants. Sericea Lespedeza will not be helpful for forage until the next year. Results show a small reduction in the yield of Sericea Lespedeza in the next year with the usage of herbicide. According to this literature, the most effective method to control the growth of Sericea Lespedeza is by using herbicides. Taking this into consideration, the herbicide treatment is considered an efficient treatment strategy for controlling the invasion of Sericea Lespedeza in this research.

Silliman and Maccarone (2005) conducted a survey in Cowley County, Kansas, to determine the spatial distribution, level of infestation, and estimated treatment cost for controlling the invasion of Sericea Lespedeza. The invasions of this weed were also determined by water distribution, soil, and forest cover. The objective was to determine those areas infested by Sericea Lespedeza. The surviving area was chosen randomly by seeking permission from landowners. Two 800-meter belt transects were used to determine the spatial distribution. Sericea Lespedeza with multiple ramets was counted as one plant. A survey conducted in the eastern part of Cowley County showed that 16 of the 20 sites were infested, which accounts for 80% of the spatial distribution. The level of infestation in each area was categorized based on the density of

Sericea Lespedeza. The treatment cost was estimated with respect to this categorization. According to 20 survey sites with water, the most common water type identified was ponds in which 12 sites were found to contain Sericea Lespedeza. High forest-cover regions have dense populations of Sericea Lespedeza. Soils are moderately sloping and well drained, and contain more Sericea Lespedeza. Their results show that Sericea Lespedeza will spread rapidly throughout the county, and its control depends on early detection and treatment of infested areas.

2.3 Growth and Dispersal

Shigesada and Kawasaki (1997) discuss the various models for the spatial distribution of invasive species. In this book, they propose the population density of invasive species based on random diffusion and population growth. Random diffusion is measured based on a diffusion coefficient, while the population growth is computed based on intrinsic growth rate and the effect of reproduction rate by competing with the native species and resources. In random diffusion, the distribution of invasive species can be observed only during the initial stage, and it becomes scattered as it grows. The diffusion coefficient remains constant throughout that time and is calculated using the distance travelled by the invasive species from the initial stage until the current time period. The logistic growth function slows down as the population reaches its carrying capacity. This book also provides another model with the combined effect of random diffusion and logistic growth, and results in an exponential increase in population density as the time period increases.

Pitt (2008) develops different models for the spread of invasive species. A geographic information system is designed to analyze the process of spatial distribution of invasive species. It assists in data collection as well as for aerial spraying. The kernel module proposes a long-distance dispersal model, which represents the probability of invasive species travelling a certain distance. A long-distance dispersal model is used for non-contiguous areas of the population. The spatial distribution of invasive species is also measured by a rate at which invasive species spread. Poisson distribution is used to generate the dispersal events. The survival module represents the probability of survival and the habitat of invasive species in patches. The growth module represents the number of individual populations in a cell and depends on the carrying capacity of the cell. Different growth equations are developed based on the population of the invasive species, intrinsic growth rate, and carrying capacity of cell. The population density increases with time by varying the intrinsic growth rate in all of the growth models. The model is selected based on the dispersal characteristics of the invasive species. After reviewing this paper, the infested land with a heterogenous population and the growth model for dispersal, which gives more detail about the invasion process, were considered.

2.4 Impact of Invasive Species

Invasive plants have a major impact on the economic, environmental, and social losses in range and wild lands. Dunkan et al. (2005), developed a questionnaire to determine the acres infested by different invasive species. Their objective was to analyze the impact of different nonnative plants in the United States. Duncan et al. (2004) shows various aspects of the environmental impact of 16 different invasive species. Among these species, the average annual spread rate of Sericea Lespedeza is shown to be very high. Sericea Lespedeza reduced the net present value of grazing land in Kansas from $726/ha for noninfested lands to $183/ha for infested land. The authors provide comprehensive information about environmental and economic impact of different species.

2.5 Control of Sericea Lespedeza by Herbicides

Koger et al. (2002) proposed three growth stages of Sericea Lespedeza: simple ramet, branched ramet, and flowering. The objective is to determine the control of Sericea Lespedeza for several years with the usage of triclopyr, fluroxypyr, and metsulfuron herbicides at different growth stages. An experiment was conducted at three different locations in central Oklahoma. Three herbicides were applied at different growth stages. A geosynchronized satellite (GSAT) was used to monitor the ramet densities over time and also compare the percentage of ramets remaining before and after treatment. The herbicides triclopyr and fluroxypyr applied during the branched-stem stage were highly effective for long-term control, with the percentage of remaining ramet less than 6%. Metsulfuron herbicide applied during the flowering stage was not suggested for long-term control, with more than 30% of ramets remaining as shown in the GSAT results. The grass biomass production was higher in all treatment plots. The seedling densities were lower in plots treated with triclopyr and fluroxypyr, but the densities were higher in the flowering stage, even after applying metsulfuron herbicide due to a greater number of available ramets. Results show that a suitable treatment must be applied during the early stages to avoid the production of seeds and therefore density of Sericea Lespedeza.

Altom et al. (1992) conducted an experiment to determine the post effect of herbicides on Sericea Lespedeza. The objective here was to evaluate the control of Sericea Lespedeza with post-mixture herbicides 2,4-D and triclopyr treatment. Herbicides were applied between May and June, and the ramets were counted on the day of treatment as well as after a year to determine the long-term control of Sericea Lespedeza by herbicides. Results show that more than 90% of ramets were eliminated after a year.

2.6 Mathematical Models for Controlling Invasive Species

The objective of the optimization technique developed in this thesis is to predict the spread and the damage generated by the dispersal of invasive species in the long-term planning horizon by considering growth and dispersal characteristics of the species. The solution to the optimization model will provide a treatment strategy to landowners to determine when and where to apply the herbicide treatments to control Sericea Lespedeza.

Govindarajulu et al. (2005) proposed a population matrix model to control the population of bullfrogs by considering different life stages. The objective of their model is to determine the survival and growth rate of bullfrogs affected by effective control methods. The population of bullfrogs was taken from four individual ponds. Capture-mark-recapture methods were used to estimate the survival and growth. Survival rates are used to set a hypothesis for the model with respect to different ponds. A population matrix model was created based on the sample size of the model, a time invariant, and the life cycle of the species. The model provides the survival and potential population growth rate with a minimum sample size and qualitatively assesses the alternate control strategies.

Olson and Roy (2002) analyzed the economics of controlling a biological invasion whose natural growth and spread is caused by environmental disturbance. The objective is to find a suitable condition that is optimal and not optimal to remove the invasive species. Growth of the invasive species is considered a logistic growth. The cost function represents the cost of treatment required to eradicate the invasive species, and the damage function represents ecological and environmental damage caused by the invasive species. The cost and damage functions are minimized with respect to the size of the invasion, which remains after control. A proposition including marginal damages and marginal cost of control based on the distribution of invasive species by environmental disturbance was developed. The literature provides the optimal condition to eradicate the invasive species with respect to marginal cost and damage. The eradication is done when marginal damage is more than marginal cost.

Taylor and Hastings (2004) proposed a density-structured model to find the optimal control strategy for a *Spartina alterniflora* invasion. The objective is to find strategies that eradicate the invasion, control costs, and manage the risks of seed production by invasive species during treatment. A multiple objective technique is used to find the optimal strategy. The population of *Spartina* is classified into seedling, clone, and meadow, with different densities. Various scenarios were used to find the optimal strategies associated with cost and risk. The first scenario is the eradication of invasive species within 5, 10, and 20 years; the second scenario is the removal of 100 seedlings per year; and the third scenario is to maintain the fertility of a different *Spartina* population. This model generates the best strategies with minimum area to be removed, thus minimizing the objective function. The authors show that the optimal control strategy depends on the biology of invasive species and the available annual resources. Results demonstrate that those areas that should be removed for early invasion, established invasion, and late invasion are 20%, 22%, and 16%, respectively. This model shows that the removal of seedlings will reduce the risk when the budget is low.

Liebhold (2000) provides an overview of population ecology for biological invasions at different stages. The objective is to provide different management approaches to control the invasive species at arrival, establishment, and spread stages. Human travel and global trade result in high arrival rates of invasive species. Invasive species are established by demographic and environmental processes. The demographic process depends upon the birth and death rate of invasive species, while the environmental process depends upon the temporary variation in the habitat. Population growth and dispersal result in the spread of invasive species. The combined diffusion and exponential growth model is used to find the spread of invading species. In this model the intrinsic growth rate (birth rate—death rate) and diffusion coefficient are assumed to be constant throughout the time and space of the spread of an invasive species. The author suggests that international quarantine and inspection are suitable management approaches during the arrival stage of invasive species. Detection and eradication approaches are used during establishment, while domestic quarantine is used during the spread of invasive species.

Grimsrud et al. (2008) proposes a bioeconomic model for an invasive weed that is diffused from its neighbors. This model considers cattle rancher and non-rancher as two separate agents. Short-distance diffusion occurs via, wind, water, and animals. Long-distance diffusion happens through trade and transportation of grasses and hay, which are contaminated by weeds or vehicles. Weeds and grasses compete for resources such as light, water, and nutrients. The objective is to choose the optimal effort level to increase the cattle stock by reducing the number of weeds. The growth of weeds depends on both density of grasses and weeds, since grasses compete with weeds. The authors use this model to control yellow starthistle, which produces 20 to 120 seeds per plant, depending on precipitation and density of the stand. The growth of the weed is computed using a logistic function with competition coefficients. Simulations are conducted to find the optimal effort level for agents at different weed levels. The authors conclude that the reduction of weed is possible by attacking the weed at an early stage of growth.

Eiswerth and Johnson (2002) propose an optimal control model for nonindigenous species. The management effort to control the invasive species is sensitive to biological and ecological factors. The objective is to develop and compare an optimal dynamic control of the population of invasive species. The numerical solution for this model is determined by conducting sensitivity analysis. Invasive species stock in a given period is related to the previous period due to the presence of reproductive parts producing seeds. The model minimizes the economic damage caused by the invasive species stock. The logistic function is used to model the growth of the invasive species. Growth of the invasive species increases as the population increases, but it begins to fall at a certain stock limit. Growth of the invasive species will be limited by the competition between the indigenous species and also by the availability of other resources such as sunlight, water, soil, and nutrients. The sensitivity of optimal management is examined by changing the variable, such as intrinsic growth rate, carrying capacity, and effectiveness of management technologies. Results of the sensitivity analysis shows that the optimal level of the management effort is sensitive to biological and ecological factors (intrinsic growth rate of invasive species and carrying capacity afforded by the invasive species). Dynamic analysis will help both public and private landowners make decisions for investments to control the nonindigenous species.

Kaiser and Burnett (2010) propose an approach to control the invasion of the brown tree snake by early detection and rapid response (EDRR). The authors use a dynamic model to search the presence of the tree snake beyond the entry-level area and compare the current benefit and search costs by using myopic and optimal searches. The myopic search strategy is used only when the current net returns exceeds the search cost. The population growth is modeled based on the population and spread using the Skellam-Fisher diffusion process. As the internal population dominates and reaches a threshold level, the growth function is represented by a logistic function. Power outages, medical costs, and biodiversity losses are potential damages caused by the tree snake. The search cost is computed by the distance travelled while searching for the tree snake throughout the cell. The objective is to minimize damage caused by the tree snake and cost of searching within the budget for EDRR. This model was implemented in Hawaii. Results suggest that the optimal search outweighs the myopic search, with a greater number of treated cells at less cost. EDRR is an aggressive approach that has saved the island for more than 30 years.

Büyüktahtakın et al. (2011) propose a dynamic nonlinear integer model and apply it to control buffelgrass, which is an invasive weed in Sonoran desert of Arizona. The objective is to minimize damage on the resources, which are at risk by the buffelgrass. The model considers a gridded landscape with cells, each having a different population. The population of invasive weeds in a cell depends upon their growth rate and the kill rate of the treatment. The growth of invasive species is determined by the logistic function and slows down as it reaches its carrying capacity. Each cell population is computed by the population within the cell and the populations from neighboring cells. The population of invasive weeds in the current period is modeled based on the application of treatment and depends upon the critical population. The labor required to treat the cell is provided by the labor constraint and also depends upon distance. Four strategies were studied and compared with respect to damage and the labor constraint. Results derived from the solution of the model suggest that the delay in initiating the treatment will increase the labor requirement. Furthermore, the authors found that treating a cell with more population more frequently will provide a long-term benefit.

2.7 Research Motivation

Most previous research focuses on growth and survival of invasive species (Govindarajulu et al., 2005). Previous research considers the growth of invasive species using the diffusion model, and different management approaches were proposed to control the invasive species (Liebhold, 2000). Kaiser and Burnett (2010) compare the effectiveness of the myopic search and EDRR. Labor and budget constraints are considered to minimize the damage of invasive weeds (Büyüktahtakın et al., 2011). Little modeling work has been published on the economic control of Sericea Lespedeza, and as of now, only chemical treatments are used to control the growth (Koger et al., 2002). None of the above research deals with the seed bank, which contributes to the major population of invasive species for several years.

This paper will provide an optimization model to control the invasion of Sericea Lespedeza by minimizing the damage caused by it. Currently there is no such optimization model for controlling the growth of Sericea Lespedeza. The objective function will minimize economic losses to hay and forage by applying herbicide treatments within the budget constraints. This model considers the longevity and germination rate of seeds, which significantly contribute to the growth of the population. In this model, the contribution of the seed bank and seed dispersal from neighbors to the population growth are considered. This model will allow landowners to decide which cells to treat based on the population.

CHAPTER 3

MATHEMATICAL MODEL

3.1 Proposed Optimization Approach

This model will provide land managers with information on the spatial distribution of Sericea Lespedeza, and the optimal time and location to apply herbicide treatment in a long-term planning horizon. The decision variable represents the decision of making treatments in an infested area, given the population of Sericea Lespedeza and the budget allocated during the time period. A gridded landscape is considered in the model, where each cell of the grid represents one acre of land. Then, an optimization model for controlling the population of Sericea Lespedeza with respect to the limited budget to cover the costs of control in each period of the planning horizon is proposed.

The model focuses on minimizing economic damage caused by Sericea Lespedeza. The revenue loss in hay and forage due to the invasion of the Sericea Lespedeza is considered as damage in the objective function. Treatment costs consist of herbicide and labor costs. The influence of a seed bank on the Sericea Lespedeza population is considered by summing the seeds produced within the cell and the seeds dispersed from outside the cell. The age of seeds and the ability of a seed to produce new plants, i.e., longevity and germination rates, are considered to incorporate the seed bank issue into the model. A logistic function is used to compute the population growth of Sericea Lespedeza. The population of Sericea Lespedeza becomes saturated when it reaches its carrying capacity (i.e., maximum number of ramets, or stems, possible in a cell). The population of Sericea Lespedeza after treatment is based on the kill rate of the treatment applied to the existing population in a cell.

3.2 Assumptions

In this model, the following assumptions are considered:

- Hay will be damaged, even if any amount of Sericea Lespedeza exists in the cell *(i,j)*.
- The dispersal of Sericea Lespedeza seeds into a cell *(i,j)* is computed considering seed dispersal from the eight surrounding cells of cell *(i,j)*.

3.3 Model Formulation

Notation

Indices/Sets

G_{ij} A rectangular array of cells with coordinate *{i,j}*, where $i \in \{1,2, \dots, m\}$ and $j \in \{1,2,...,n\}$

T Time interval

t Three years period of the time interval, where $t \in \{0,1, \dots, T\}$

M The set defining the eight locations of the neighborhood of a cell *{i,j}*, namely *(i+k,j+l)*, where *(k,l)* ∈ M = $\{(1,1), (1,0), (0,1), (-1,-1), (-1,0), (0,-1), (-1,1), (1,-1)\}$

Parameters

Lc Labor cost per cell *(i,j)*

Hbc Herbicide cost per cell *(i,j)*

$C_{ij}(t)$ Cost of treatment for cell *(i,j)* in period *t*

B Total budget allotted to control Sericea Lespedeza

S Number of seeds produced per plant

L Longevity rate of seeds in seed bank

GR Germination rate of seeds in seed bank

DR Survival rate of plants from seedlings

RS Percentage of remaining seeds after dispersal in cell *(i,j)*

$\lambda_{(i,j)}(t)$ Percentage of seeds travelling to cell *(i,j)* from surrounding cell *(i+k,j+l)*, where *(k,l)* ∈ M in period *t*

ω_{ij} Kill rate of herbicides in cell *(i,j)*

H_{ij} Revenue from hay per period from cell *(i,j)*

F_{ij} Revenue from forage per period from cell *(i,j)*

r Intrinsic growth rate

K_{ij} Carrying capacity of cell *(i,j)* i.e., maximum number of ramets of Sericea Lespedeza that can occur in cell *(i,j)*

Continuous Decision Variables

$D_{ij}(t)$ Damage function in cell *(i,j)* in period t

$Seed_{ij}(t)$ Number of seeds produced in cell *(i,j)* in period t

$Seed'_{ij}(t)$ Number of seeds dispersed from surrounding cells *(i+k,j+l)* to cell *(i,j)* in period *t*, where *(k,l)* ∈ M

$Seed\ Bank_{ij}(t)$ Number of seeds in seed bank of cell *(i,j)* in period *t*

$N_{ij}(t)$ Population of Sericea Lespedeza in cell *(i,j)* in period *t*

$N'_{ij}(t)$ Proportion of Sericea Lespedeza population to carrying capacity $(N_{ij}(t)/K_{ij})$ in cell *(i,j)* in period *t*

$N_{ij}^{B}(t)$ Population of Sericea Lespedeza before treatment in cell *(i,j)* in period *t*

Binary Decision Variables

$g'_{ij}(t)$ {1, if $N_{ij}(t) > 0$; else 0}

$x_{ij}(t)$ {1, if cell *(i,j)* is treated in year t; else 0}

3.3.1 Damages and Objective Function

Grazing and haying are limited to young Sericea Lespedeza (Kansas Department of Agriculture, 2010). When Sericea Lespedeza becomes over mature, the forage quality gets poor (Gucker, 2010). Reduced grass forage quality means losses in land value and livelihood for cattle ranchers.

Damages are considered as an economic loss caused by Sericea Lespedeza infestation. Sericea Lespedeza is capable of producing a large number of seeds every year, and this seed production increases further after the third year of establishment. Therefore, in order to consider the revenue loss in hay and forage, damage is considered over all periods, each of which corresponds to three years. In this model, damage is computed for three periods by considering two main factors:

- Forage: Sericea Lespedeza is recognized for its high level of crude protein. However, due to its high tannin content and indigestible nature, it becomes difficult for animals to graze. This results in poor quality forage, thus reducing the revenue from forage. In this model, forage loss is computed by multiplying the proportion of the Sericea Lespedeza population in a given cell to the maximum possible population in that cell.
- Hay: Haying is one of the contributors to the dispersal of Sericea Lespedeza due to transportation of its seeds from one place to another (Ohlenbusch et al., 2007). Furthermore, the presence of Sericea Lespedeza seeds in hay reduces the hay value. This model considers the loss in hay value in a particular cell, even if a single Sericea Lespedeza ramet is observed in that cell.

The objective function is to minimize the total economic loss (damage) caused by Sericea Lespedeza over all cells of the grid during a time interval (T). The economic loss by Sericea

Lespedeza is the average monetary value of haying and grazing in a cell because the grass is used for either haying or grazing. The hay damage value is computed by considering the presence of Sericea Lespedeza in a cell *(i,j)*, while the forage damage value is calculated based on the proportion of Sericea Lespedeza in a cell *(i,j)*. The objective function is then given as

$$\text{Minimize } \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{t=1}^{T} D_{ij}(t) \qquad (3.1)$$

where the damage (economic loss) function has the following form:

$$D_{ij}(t) = (H_{ij} * g'_{ij}(t) + F_{ij} * N'_{ij}(t))/2 \quad \forall\, i, j, t. \qquad (3.2)$$

3.3.2 Seed

Seed Generation within Cell

According to Woods et al. (2009), Sericea Lespedeza produces seeds at a rate of 150 to 300 million per acre in cultivated stands, which in turn lead to 900 seeds produced by a single Sericea Lespedeza ramet. Although seed production in natural areas is likely to be less than this amount, it is an important factor to consider in the management of Sericea Lespedeza populations.

Now seeds within the cell are computed by the seeds produced from the available ramets in the cell, which remain in the cell after dispersal. The number of seeds is given as

$$Seed_{ij}(t) = N_{ij}(t) * S * RS \quad \forall\, t \qquad (3.3)$$

Seed Dispersal Outside Cell

The dispersed seed population in a cell *(i,j)* is computed by considering the Sericea Lespedeza seeds travelling to cell *(i,j)* from eight surrounding cells *(i+k,j+l)*,where $(k, l) \in M$. The number of seeds dispersed is given as

$$Seed'_{ij}(t) = S * [\sum_{(k,l \in M)} \lambda_{(i+k,j+l)}(t) * N_{(i+k,j+l)}(t)] \quad \forall\, i, j, t \qquad (3.4)$$

Seed Bank

Sericea Lespedeza seeds are viable in the soil for many years. Longevity is the life expectancy of seeds. Those seeds that are viable and not germinated as a plant and those seeds dispersed from the surrounding cells are included in the current seed population of the cell. In particular, the population of seeds in a seed bank is computed by considering their longevity, those seeds that are not germinated within the cell, seeds travelling from surrounding cells, and the initial seed bank population. The longevity and the germination of seeds are inversely proportional to the age of seeds. This important component is also considered in determining the number of seeds in the seed bank function equation, which is given as

$$SeedBank_{ij}(t)=\sum_{k=0}^{t}(L-GR)^{(t-k)}*[Seed_{ij}(k)+Seed'_{ij}(k)]+[SeedBank_{ij}(0)*(L-GR)] \quad \forall\, t \qquad (3.5)$$

3.3.3 Population Growth Function

In this model, the population growth has been modeled using a logistic growth function. The population before treatment is computed by taking the minimum of the current population obtained by the logistic growth of Sericea Lespedeza and the population germinated from seeds in the seed bank and the carrying capacity. Before treatment, the population is obtained by the following equation:

$$N_{ij}{}^{B}(t+1)=Min\begin{cases}[N_{ij}(t)*(K_{ij}*e^{r})]/[K_{ij}+(N_{ij}(t)(e^{r}-1)]+[SeedBank_{ij}(t)*GR*DR] \\ K_{ij}(t)\end{cases} \forall\, t>=0 \qquad (3.6)$$

3.3.4 Population after Treatment

The after-treatment population of Sericea Lespedeza is computed by reducing the value of the before-treatment population by the kill rate of the herbicides, if treatment is applied. The after-treatment population will be the same as the before-treatment population, if no treatment is applied. After treatment, the population is obtained by

$$N_{ij}(t) = N_{ij}^{B}(t)\left(1-\omega_{ij}*x_{ij}(t)\right) \quad \forall\, t \qquad (3.7)$$

3.3.5 Budget Constraints

Because Sericea Lespedeza establishes quickly, subsequent monitoring and follow-up treatments are likely necessary for its long-term control. Sericea Lespedeza is controlled by applying suitable herbicides. Treatment cost is associated with the cost of labor and herbicides. This model predicts the requirement of treatment in a particular period while minimizing the objective within the budget limits. The treatment in a particular period is done based on the population of Sericea Lespedeza in each of the cells within the grid.

The budget constraint ensures that the cost of treatment over all cells of the grid must be less than or equal to budget allocated in the planning horizon given as

$$\sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{t=1}^{T} C_{ij}(t) * x_{ij}(t) \leq B \tag{3.8}$$

where

$C_{ij}(t) = Tc * N'_{ij}(t)$

$= (Lc + H_b c) * N'_{ij}(t)$

CHAPTER 4

CASE STUDY

4.1 Background

Sericea Lespedeza, a perennial legume native to Asia, was introduced into the United States by the USDA in 1900. It was planted on strip-mined areas in southeast Kansas. It is recognized for its tolerance of drought, acidity, and shallow soils of low fertility. It was introduced for erosion control, livestock forage, and wildlife cover. Sericea Lespedeza produces seeds that remain viable for many years. Woods et al. (2009) reported that Sericea Lespedeza produces at least 900 seeds per ramet. Sericea Lespedeza is deep rooted. It grows from April through September.

Sericea Lespedeza contains high levels of crude protein, including a high concentration of tannin. The tannin level in Sericea Lespedeza increases as the plant grows, leaving them undigestable. According to Ohlenbusch et al. (2007), deer consume Sericea Lespedeza only when they are young, and quail eats its seeds during the fall and early winter. However, Sericea Lespedeza seeds do not have the ability to produce sufficient energy for quail to be sustained in poor weather conditions. Sericea Lespedeza provides wildlife cover, but when dormant, the cover will be lacking because other plants are excluded. Once established, Sericea Lespedeza will reduce the growth of native plants. It restricts the amount of light reaching other plants, consumes more water, and produces an allelopathic chemical, which inhibits the seed germination and growth of other plants (Ohlenbusch et al. (2007).

The overgrazing of native plants occurs due to the unpalatable nature of Sericea Lespedeza, which contains a high content of tannin. According to Stitt (1943), 6% of the tannin content remains in a 4-inch plant and 21% in a 36-inch plant. Cattle will not graze when Sericea

Lespedeza grows more than 4 to 6 inches tall. Marsh (2012) conducted a study to determine the long-term impact of Sericea Lespedeza on grazing lands, reporting a reduction in 30 year net present value of grazing land in Kansas from $294 per acre for non-infested land to $74 per acre for infested land. It has been found that the average annual forage loss in the Flint Hills region of Kansas due to Sericea Lespedeza is $29 million (Marsh, 2012) . In 2001, the state of Kansas declared it a noxious weed.

Sericea Lespedeza is increasingly spreading, with approximately 8.6 million acres of land invaded by Sericea Lespedeza across the United States (USDA NRCS Plant Materials Program, 2006). According to Nabors (1996), 11% of the Great Smoky Mountains National Park in Tennessee has been occupied by Sericea Lespedeza. Ohlenbusch et al. (2007) predicts an increase of 24% in the population of Sericea Lespedeza in Kansas within 14 years. These statistics show a great threat of invasion across the U.S.; therefore, it becomes essential for landowners to control this weed.

4.2 Control Techniques

Sericea Lespedeza is a prolific seed producer, and seeds are viable for many decades. Even though the plants are eradicated through suitable treatments, the seeds remain viable in the seed bank. The ability of seeds to germinate will further help in establishing the population of Sericea Lespedeza. Therefore, multiple treatments over several seasons are required in order to completely eradicate this weed. Controlling of Sericea Lespedeza should be prioritized with respect to the density in the area.

Conventional management practices to control Sericea Lespedeza are fire, grazing, and mowing. Burning in late spring followed by intensive early stocking may reduce the occurrence of Sericea Lespedeza. Houseman et al. (2012) conducted an experiment to determine the effect of fire on Sericea Lespedeza germination and seedling survival. Results show an increase in the germination rate of seeds in the fields and a small decrease in survival rate. According to Gucker (2010), fire will promote the seed germination. Grazing during April and May in infested areas with sheep and goats will help in controlling the growth of Sericea Lespedeza. According to Ohlenbusch et al. (2007), it is not advisable to graze Sericea Lespedeza during fall and winter due to its unpalatable nature and high seed production during the season. Grazing during fall and winter may lead to an increase in the dispersal of seeds by sticking to the animals' bodies. Late grazing will increase the population of Sericea Lespedeza, while frequent mowing will reduce the population. Sericea Lespedeza should be mowed before it reaches a height of 12 to 18 inches. However, mowing may also reduce the cover of native grasses.

Invasive species are also controlled by a biological control method by considering many factors. Lespedeza webworm (*Tetralopha scortealis*) is used as a biological control agent. Lespedeza webworm is an herbivore that reduces the photosynthetic ability of plants. Gucker (2010) proposed the reduction in seed production by 98% by using Lespedeza webworm. However, Lespedeza webworm may affect native species.

Herbicides are used to control the growth of Sericea Lespedeza. Koger (2002) proposed that triclopyr, metsulfuron, and fluroxypyr are suitable herbicides for controlling the growth of Sericea Lespedeza. Triclopyr is applied during the flowering stage, from July to August. Metsulfuron is applied in mid-September. The effect of herbicides is reduced as the result of heat and drought conditions. Even though these herbicides are very effective in reducing the ramet densities of established Sericea Lespedeza, factors such as prolific seed production and viability of seeds in the seed bank could influence reestablishment of Sericea Lespedeza.

4.3 Data Collection

To collect data, a gridded landscape model is considered. Each cell of the grid represents one acre. A 10 by 10 rectangular array of cells is considered to represent the grid. Land size is taken in acres while evaluating and collecting Sericea Lespedeza data.

Carrying Capacity

Carrying capacity is the maximum Sericea Lespedeza population that can occur in an acre of land, considering competition with native species, soil, and other resources. The proportion of Sericea Lespedeza in a cell will provide information on population growth and damage that has occurred. The population of Sericea Lespedeza in a cell may change with respect to the treatment applied during the time period. Based on the Houseman (2012) experiment, a maximum of 1,936,000 Sericea Lespedeza plants can exist on an acre of land.

Intrinsic Growth Rate

The intrinsic growth rate specifies the maximum rate at which Sericea Lespedeza grows between successive time periods. This rate depends upon the previous year's population and the capacity to recover after depletion to reach its carrying capacity. The intrinsic growth rate value (20.4) is quite high for Sericea Lespedeza and implies that carrying capacity will be met very rapidly (Schutzenhofer et al., (2009).

Seed Production

Sericea Lespedeza is a prolific seed producer. Woods et al. (2009) examined the production of Sericea Lespedeza seeds per plant and reported, on average, between 6,500 to 8,000 seeds per plant, or roughly 900 seeds per ramet (stem).

Longevity

Longevity of seeds is the ability of the embryo to germinate and depends on a number of different conditions. There is very limited information on the longevity of Sericea Lespedeza. Research is needed to determine how long Sericea Lespedeza seeds can remain viable in soil. In an attempt to accommodate the effect of a long-lived seed bank, one can track the historical seed production within a cell and apply a variable to decay this seed bank overtime, because seeds will be lost to a number of variables, including fungi and animal consumption. After considering the characteristics of Sericea Lespedeza, it has been assumed that 95% of seeds remain viable in the seed bank. This percentage will be adjusted, and its effect on the output of the model will be assessed.

Germination Rate

Germination rate is the percentage of seeds of a species that will germinate to become a plant. Seed germination depends on its viability rate, death rate, and environmental effects (Baskin and Baskin, 1998). Sericea Lespedeza seeds are not penetrable, so they are scarified to increase the germination (Ohlenbusch, et al., 2007). According to Houseman et al. (2012), the germination rate of freshly sown Sericea Lespedeza seeds is roughly 6.8%. They conducted the experiment by varying the number of seeds sewn into multiple test plots. In order to obtain the germination rate through one growing season, the number of sprouts was counted and compared to the number of seeds sown.

Dispersal of Seeds

Seeds are dispersed from one location to another by natural and mechanical disturbances. There is no specific pattern for seed dispersal, and the dispersal of seeds plays an important role on its invasion (Smallwood, 1984). The dispersal rate of Sericea Lespedeza is unknown. In order to model a population's geographical spread, a certain number of seeds are assumed to migrate beyond the cell in which they were produced. A rectangular grid in which each cell represents one acre of land is considered. The percentage of seeds traveling out of a cell is set at 76%, and the percentage of seeds traveling into a cell from surrounding cells is 3%. The seed dispersal percentage assumption considers the characteristic and historical records of Sericea Lespedeza invasion. These will be adjusted, and their effect on the output of the model will be assessed.

Labor Cost

Labor rates for herbicide application can vary slightly depending on the applicator. The price used in this model is based on the per acre rates charged by (Asch, 2012).

Herbicide Cost and Kill Rate

Herbicides used to kill standing growth of Sericea Lespedeza are primarily metsulfuron- and triclopyr-based herbicides, such as Ally and Remedy (Kansas State University, 2012). Herbicide cost varies with respect to application. The kill rate of these herbicides is nearly same. Under the proper conditions and application rates, either of these types is capable of achieving a 95% to 99 % kill rate (Lance et al., 1997).

Revenue—Hay and Grazing

Taylor and Hastings (2004) calculated the revenue possible from one acre of grassland based on haying and grazing. Hay and grazing is based on price per acre. Local haying yields must be taken into account in order to appropriately scale hay revenue into the model.

Budget

The budget for treating Sericea Lespedeza is not fixed. The Kansas State Department of Agriculture reports an estimate of $1.15 million, which was spent on controlling Sericea Lespedeza in 2011 (Marsh, 2012).

The data collection of Sericea Lespedeza is outlined in Table 4.1

Table 4.1: Data Collection of Sericea Lespedeza

Symbol	Definition	Unit	Value	Resources
K_{ij}	Carrying capacity in cell *(i,j)*	ramets/acre	1,936,000	Houseman, 2012
r(t)	Intrinsic growth rate in period *t*.	ramets/year	20.4	Schutzenhofer, Valone, & Knight, 2009
S	Number of seeds produced per plant	seeds/ramet	900	Woods, Hartnett, & Ferguson, 2009)
L	Longevity	N(T)/N(T-1)	95%	Best educated guess
GR	Germination rate	seedlings/ seeds	6.80%	Houseman, 2012
RS	Percentage of remaining seeds which are not dispersed outside cell *(i,j)*	seeds/seeds	76%	Best educated guess
Lc	Labor cost	$/acre	$3.25	Asch, 2012
Hc	Herbicide cost	$/acre	$10.50	Kansas State University, 2012
Λ	Percentage of seeds travelling from surrounding cells	seeds/seeds	3%	Best educated guess
Hij	Revenue from hay in cell *(i,j)*	$/acre	$8.61–$25.53	Kansas State University, 2004
Fij	Revenue from forage in cell *(i,j)*	$/acre	$29.10–$81.71	Kansas State University, 2012
Ωij	Eradication rate/kill rate	percent	$95 < \alpha < 99$	Lance, Terrence, & Stritzke, 1997

4.4 Solver

The mathematical model is coded in AMPL in order to solve the complexity of the model and to perform the experiments on a large scale. The model was coded in the Mod file, and the collected data was presented in the Data file. The experiment was conducted using these files, and the preliminary results are shown in section 4.5.

4.5 Data Generation

The reliability of a mathematical model for a specific application is determined by comparing the results of that particular model with respect to practical cases. Data collection and generation are important factors for conducting an experiment. In this thesis, the initial population of the Sericea Lespedeza is categorized based on the percentage area invaded and the density of the population in the invaded area. These two impotant characteristics are described below:

Percentage Area Invaded

Invasion of a species depends on its characteristics, dispersal rate, and natural condition. The invasion of Sericea Lespedeza varies moving from east to the west across the various counties of Kansas (Kansas Department of Agriculture, 2010). In the experiments, different types of initial population are defined as an input to the model, and they are categorized by the invasion percentage, which defines the percentage of cells infested by Sericea Lespedeza. The invasion percentage varies between 10% and 80%. Table 4.2 shows the categorization of initial population based on the invasion percentage in a cell.

Table 4.2: Classification of Initial Population Based on Invasion Percentage

Description	Invasion (%)	Initial Population
Spread of Sericea Lespedeza across All Areas	10	Very Low Initial Population
	20	Low Initial Population
	40	Medium Initial Population
	80	High Initial Population

Intensity of Invasion

Native species are also affected by the amount of Sericea Lespedeza available in the particular area. Damage caused in a particular area is positively correlated with the intensity of Sericea Lespedeza, which is defined by the amount of plants in that particular area. Table 4.3 shows the categorization of the initial population based on the number of Sericea Lespedeza stems in a cell.

Table 4.3: Classification of Initial Population based on Density of Population

Description	Intensity (stems per cell)	Initial Population
Number of Sericea Lespedeza in a Cell	1–9	Very Low Initial Population
	10–19	Low Initial Population
	20–29	Medium Initial Population
	30–40	High Initial Population

The intensity of Sericea Lespedeza in each cell is determined by generating a random number of ranges, as specified in Table 4.3 under the intensity column, and also by considering the percentage of area invaded, as specified in Table 4.2, with respect to different initial populations. The distribution of population in each cell is considered with respect to the percentage of area invaded. For example in Table 4.4, for a 10 x 10 grid cell, the percentage of area invaded is considered to be 10%, with the population ranging from 1 to 9. The population in the remaining 90% of cells is considered to be zero. Tables 4.4 to 4.7 show both the distribution of the invasion and its intensity level for different initial populations based on the information provided in Tables 4.2 and 4.3.

Table 4.4: Distribution of Very Low Initial Population

VERY LOW POPULATION (10% invasion)										
CELL	1	2	3	4	5	6	7	8	9	10
1	9	0	0	0	0	0	0	0	5	0
2	7	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	3	10	9
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	5	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	3	0	0	0
10	0	0	0	0	0	0	0	0	0	6

Table 4.5: Distribution of Low Initial Population

LOW INITIAL POPULATION (20% Invasion)										
CELL	1	2	3	4	5	6	7	8	9	10
1	12	13	0	0	0	13	0	18	0	0
2	0	0	0	0	0	0	18	0	0	0
3	0	0	0	0	14	0	0	0	0	13
4	12	0	0	18	0	0	0	0	0	18
5	0	10	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	18	0	0	0	0	17	0	0	0	18
8	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	10	0
10	0	0	16	0	11	14	0	0	10	11

Table 4.6: Distribution of Medium Initial Population

MEDIUM INITIAL POPULATION (40% Invasion)										
CELL	1	2	3	4	5	6	7	8	9	10
1	27	0	22	0	0	0	0	0	0	25
2	0	20	0	0	0	22	20	25	0	29
3	24	0	25	0	0	26	0	27	0	0
4	0	0	0	0	0	27	0	23	0	0
5	0	20	0	0	27	0	23	0	27	0
6	0	0	22	23	0	26	27	0	0	0
7	21	29	0	0	22	0	29	0	0	0
8	21	0	0	24	22	25	20	27	29	0
9	0	29	27	0	0	0	28	0	0	25
10	0	29	0	0	20	0	27	0	0	0

Table 4.7: Distribution of High Initial Population

HIGH INITIAL POPULATION (80% Invasion)										
CELL	1	2	3	4	5	6	7	8	9	10
1	38	37	31	34	33	0	38	32	30	40
2	30	33	0	0	33	37	30	37	33	39
3	0	0	0	30	32	39	40	0	40	38
4	38	32	39	31	30	0	39	32	40	0
5	36	31	32	37	38	35	0	0	34	35
6	35	31	0	33	33	40	38	35	30	35
7	40	37	39	35	32	37	35	30	35	35
8	32	32	0	32	37	0	40	40	40	31
9	31	0	38	34	39	39	32	34	31	37
10	34	35	0	30	35	0	37	0	38	39

4.5.1 Analysis of Specific Strategies

The model was examined by conducting various experiments with different initial populations, budgets, herbicides kill rates, and dispersal rates.

Budget

The experiments were conducted for different initial populations. The damage value for each case was different, so the budget required to reduce the damage changes with respect to the initial population. The budget is categorized as very tight, tight, moderate, and ample, and its value is taken from the results obtained from experiment 1 for a different initial population.

Kill Rate

The kill rate of herbicides used for Sericea Lespedeza is 90–99%. An experiment is conducted by considering the kill rates of 90%, 95%, and 99% to determine the damage caused at different initial infestations.

Dispersal Rate

Each invasive species has its own dispersal pattern. Since the dispersal rate of Sericea Lespedeza is unknown, an experiment is conducted by considering different dispersal rates to analyze the impact of dispersal on damage over different budgets. The considered dispersal rates are 0.001, 0.005, and 0.03.

4.6 Results

In this section, we present computational results regarding the impact of different parameters such as budget, kill rate and dispersal rate. Sensitivity analyses are performed to provide insights about the problem.

4.6.1 Expected Damage over Budget with Different Initial Population

In this experiment, different invasion distributions and initial populations of Sericea Lespedeza are considered, and the corresponding damage over the three-year period is plotted with respect to the changing budget. Figures 5.1 to 5. 4 show the damage caused by Sericea Lespedeza with respect to changing budgets for four different initial populations: very low, low, medium, and high initial populations. It can be seen that with any initial populations, the damage reduces as the budget increases. Figures 5.1 to 5. 4 show that damage reduction occurs very rapidly in the beginning and becomes stabilized as the budget increases. This experiment gives land managers some idea about possible damages that will occur and the budget required to reduce the damage to a certain desired level with respect to infested land. For example, a budget of $250 is sufficient to reduce the damage to zero for very low initial population in 100 acres of land. On other hand, a minimum of $3,500 to $4,000 is required to reduce the damage to zero for a high initial population on the same land.

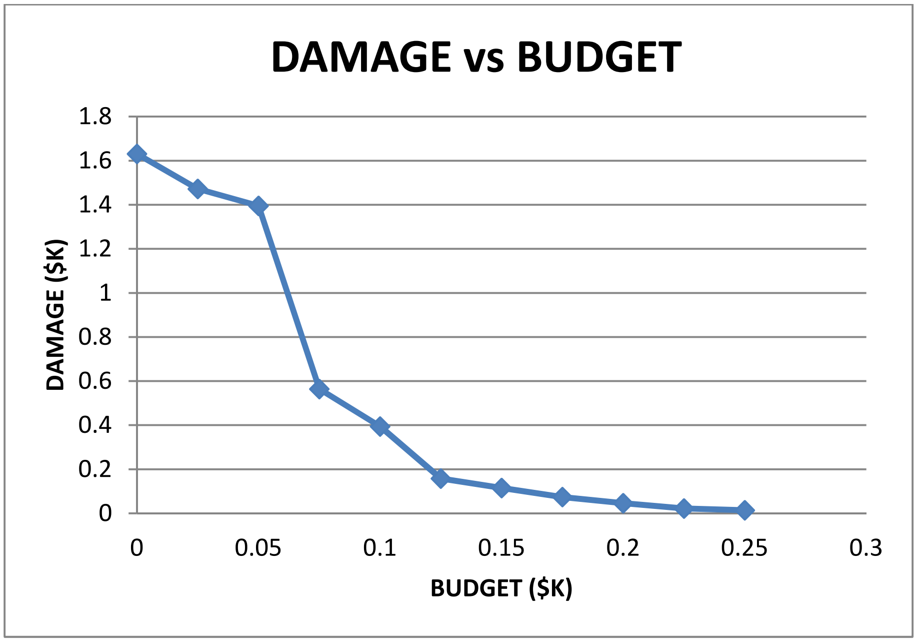

Figure 5.1 - Effect of Budget on Damage in Very Low Initial Population

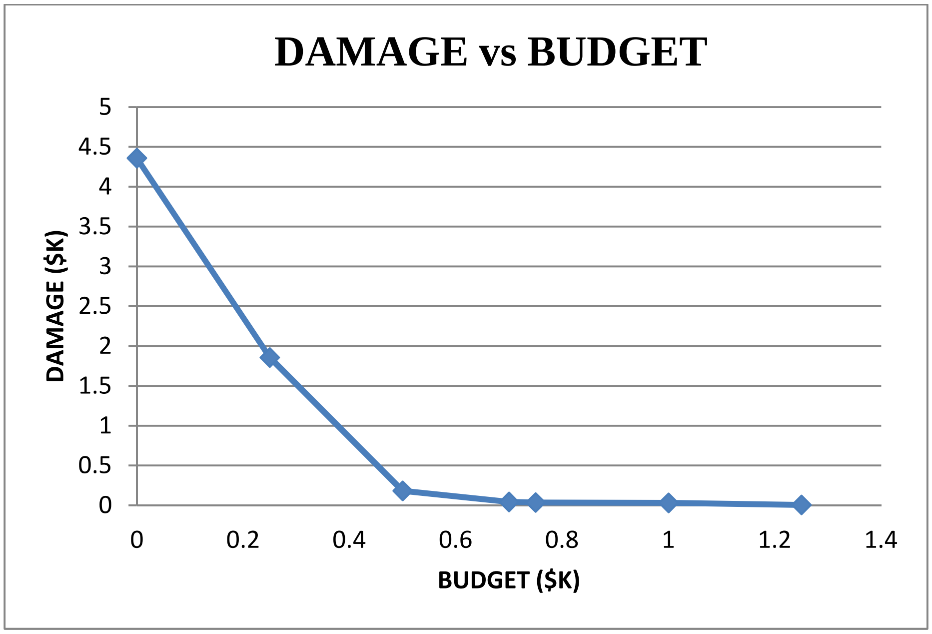

Figure 5.2 - Effect of Budget on Damage in Low Initial Population

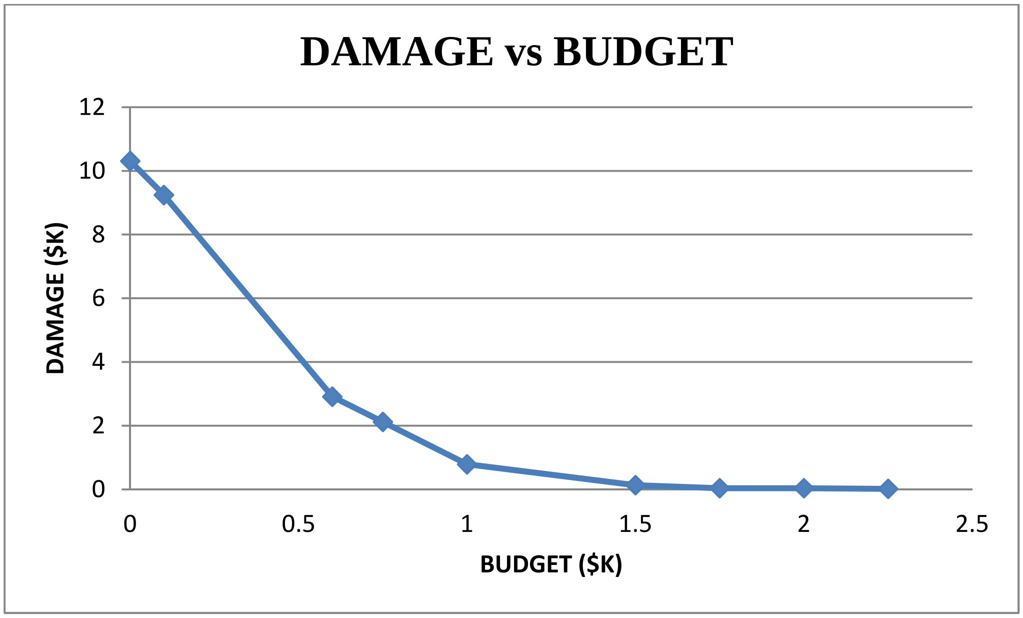

Figure 5.3 - Effect of Budget on Damage in Medium Initial Population

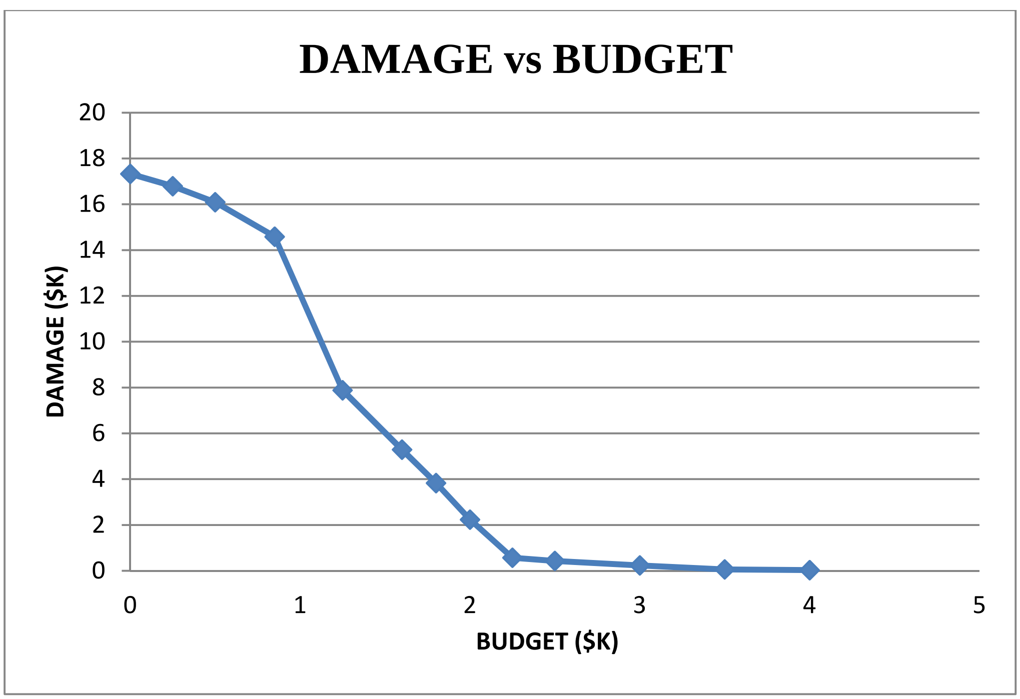

Figure 5.4 - Effect of Budget on Damage in High Initial Population

4.6.2 Expected Damage with Different Kill Rates and Budget Values

In this experiment, three different kill rates (90%, 95%, and 99%) are considered to determine how the damage function reacts with different initial populations over a three-year period with respect to a changing budget. Figures 5.5 to 5.8 show the effect of different kill rates on the damage-budget relationship in different initial population cases. It can be seen that there are very few differences in damage value in very low and low initial population cases for different kill rates. However, as the initial population increases, the difference in damage value is more noticeable for different kill rates. In Figure 5.7, for medium initial population, there is a high difference in damage value for different kill rates. However, the difference decreases as the budget reaches $1,500 for a kill rate of 90% and 99%, and it is reduced to zero after reaching a desired budget level. In Figure 5.8 for a high initial population, the damage value remains same for all kill rates in the beginning, and the difference in damage value increases as the budget increases for different kill rates. This experiment shows that a 99% kill rate provides a better reduction in damage than 90% and 95% kill rates. This experiment will help land managers to understand the effectiveness of treatment for different initial populations.

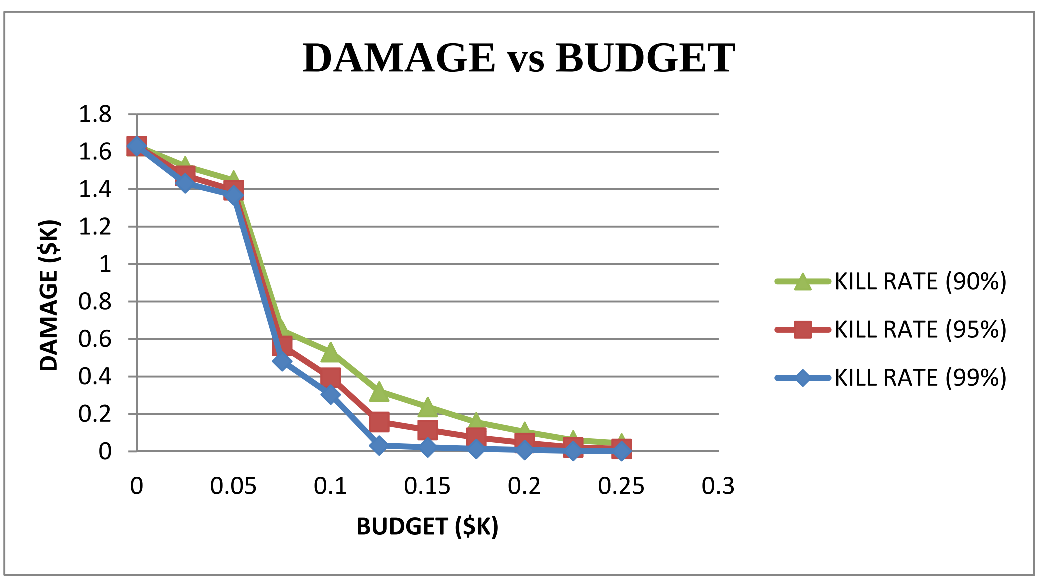

Figure 5.5 - Effect of Kill Rate on Damage over Budget with Very Low Initial Population

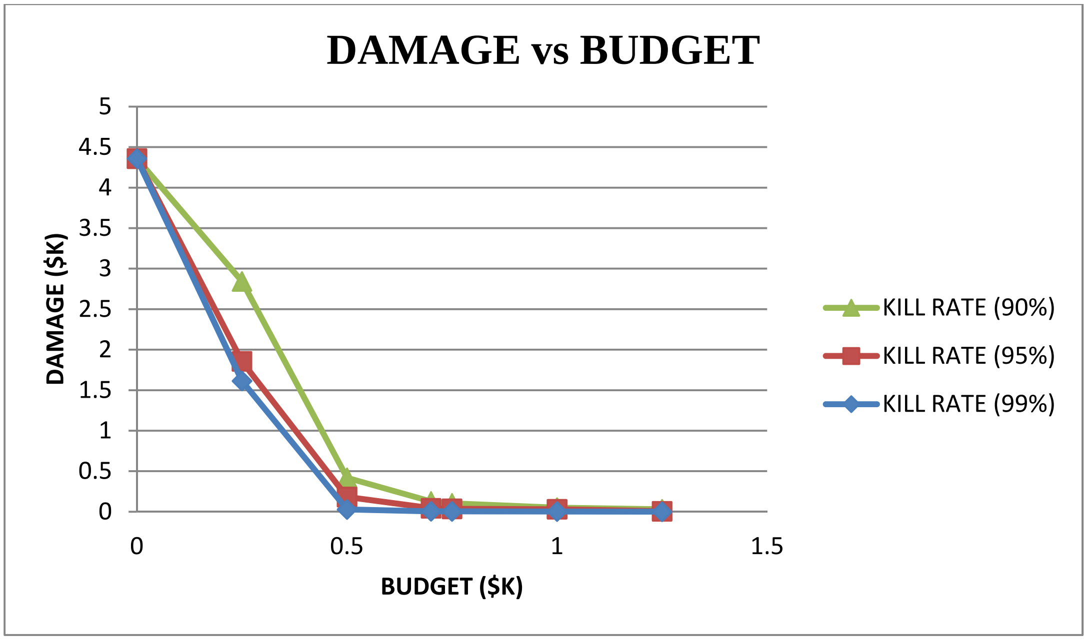

Figure 5.6 - Effect of Kill Rate on Damage over Budget with Low Initial Population

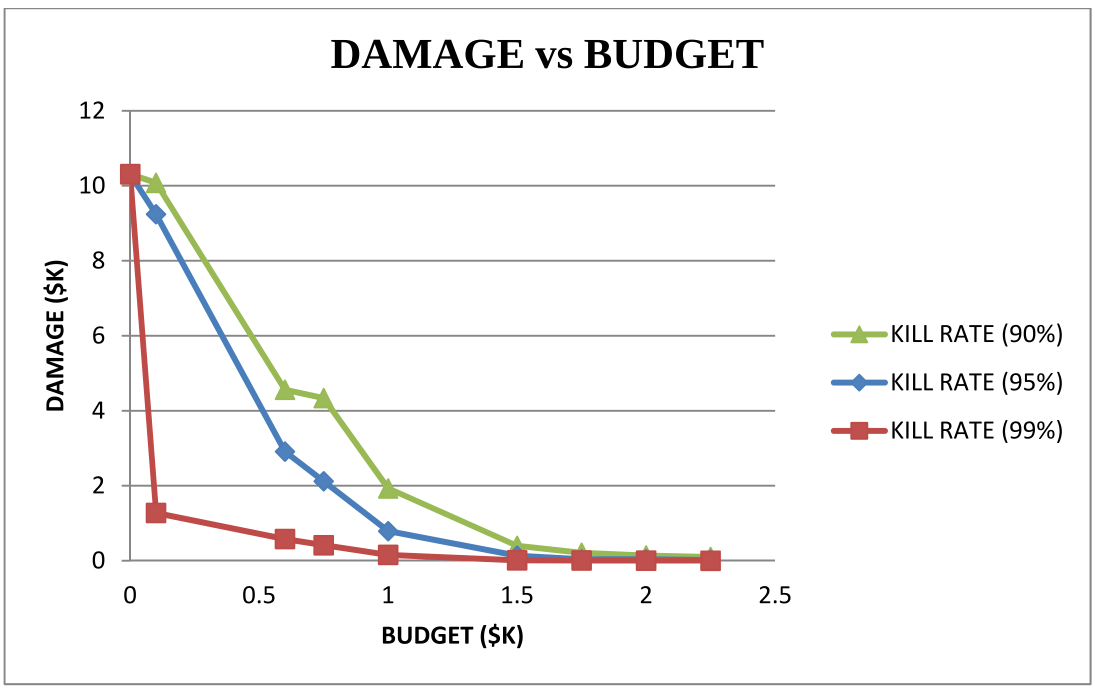

Figure 5.7 - Effect of Kill Rate on Damage over Budget with Medium Initial Population

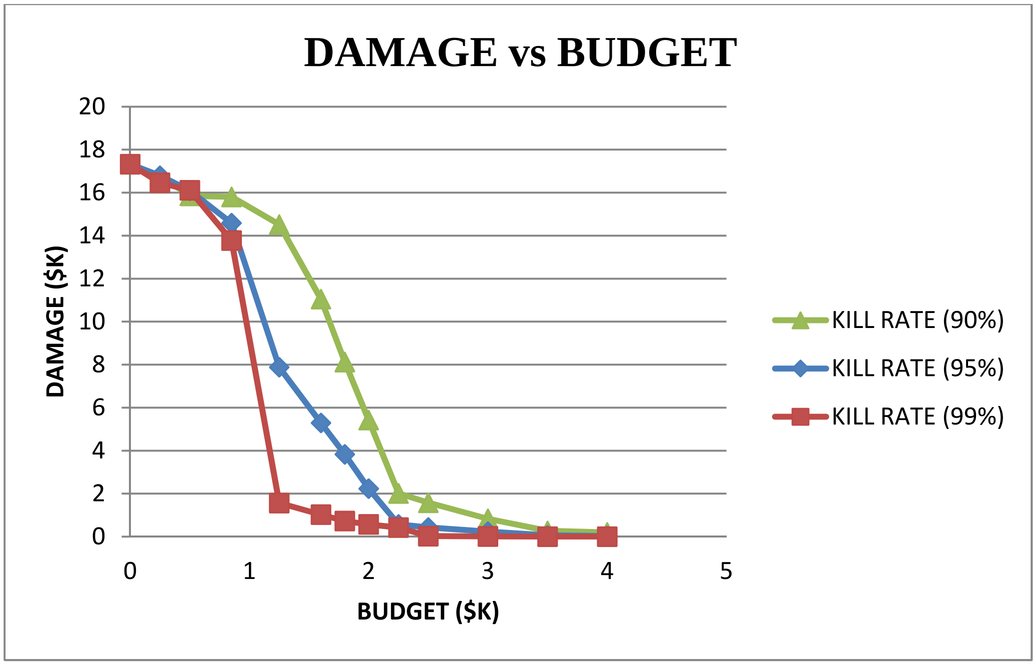

Figure 5.8 - Effect of Kill Rate on Damage over Budget with High Initial population

4.6.3 Expected Damage in Time Periods Based on Changing Budget Values

In this experiment, the damage occurring in each time period (three years) is determined with different budgets allotted during each period. Figures 5.9 to 5.12 show the damage of Sericea Lespedeza over each year with respect to very tight, tight, moderate, and ample budgets for four different initial populations. Figure 5.9 shows that some increase in damage is observed from period one to two for very tight, tight, and medium budgets. The damage value increases from the second period to the third period for all different initial populations and all budget levels, and the increase in damage value is high for very tight and tight budgets. Figures 5.9 to 5.12 show that ample and moderate budgets are more effective in reducing damage, as expected. This experiment shows that the annual damage caused by Sericea Lespedeza changes for each time period, with the increase in the initial population for different budget levels. This experiment will give land managers an idea about the yearly impact of Sericea Lespedeza for different budget levels allotted.

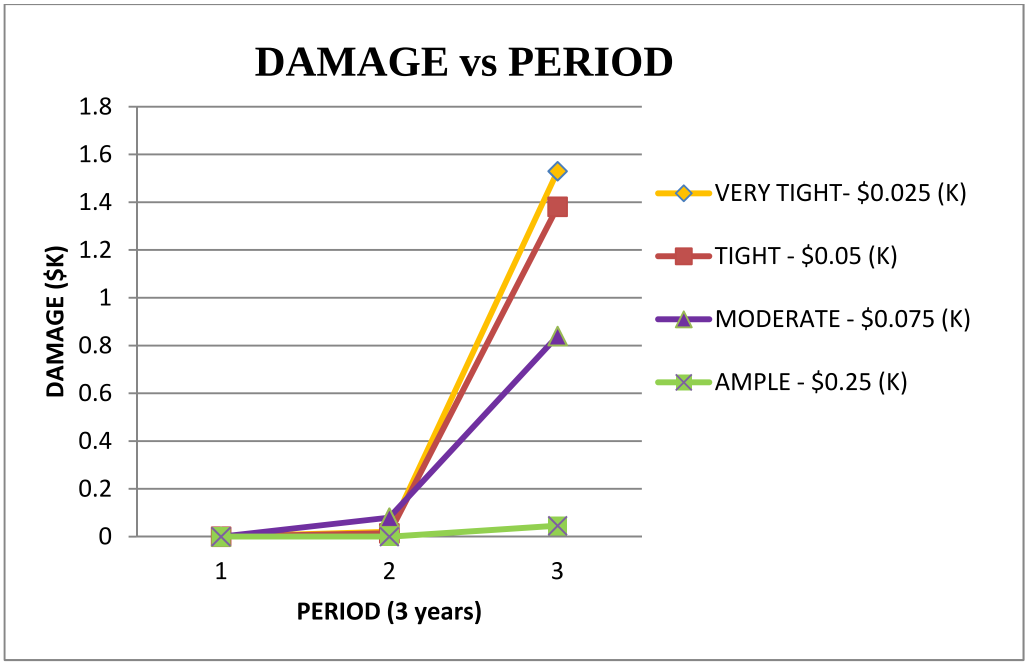

Figure 5.9 - Effect of Budget on Damage over Each Period with Very Low Initial Population

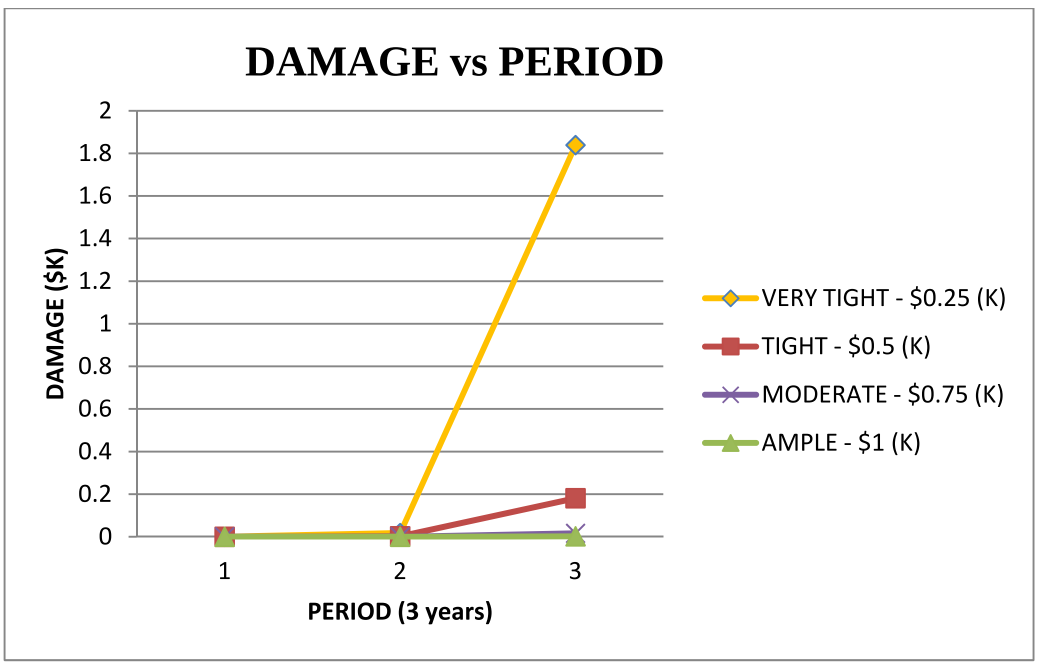

Figure 5.10 - Effect of Budget on Damage over Each Time Period with Low Initial Population

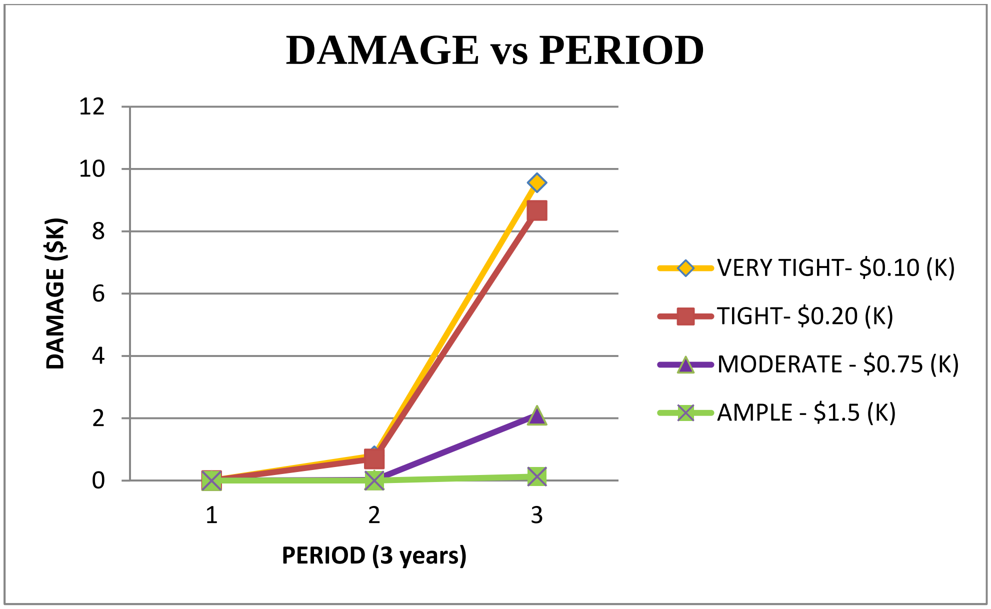

Figure 5.11 - Effect of Budget on Damage over Each Time Period with Medium Initial Population

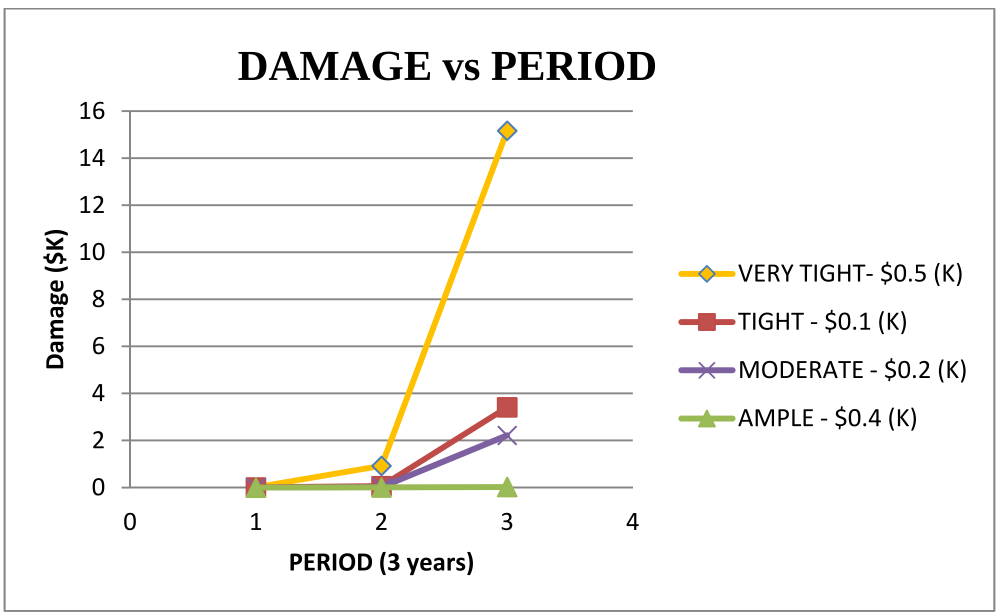

Figure 5.12 - Effect of Budget on Damage over Each Time Period with High Initial Population

4.6.4 Expected Damage over Budget with Different Dispersal Rates

In this experiment, different dispersal rates on the damage over a changing budget are considered. Figures 5.13 to 5.16 show the change in damage value for dispersal rates of 0.001, 0.005, and 0.03, with respect to different budgets. The damage in different initial populations is less when the dispersal rate is low. The difference in damage value for dispersal rates of 0.001 and 0.005 increases as we move from low initial population to high initial population. This experiment shows that the damage caused by Sericea Lespedeza is higher for the dispersal rate 0.03, and there is not much difference in the damage value with respect to dispersal rates 0.001 and 0.005.

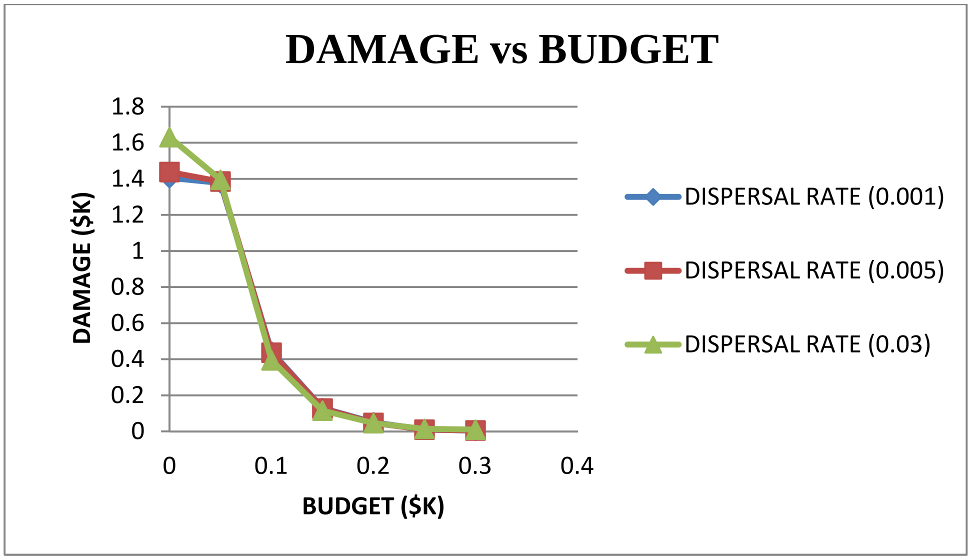

Figure 5.13 - Effect of Dispersal Rate on Damage over Budget with Very Low Initial Population

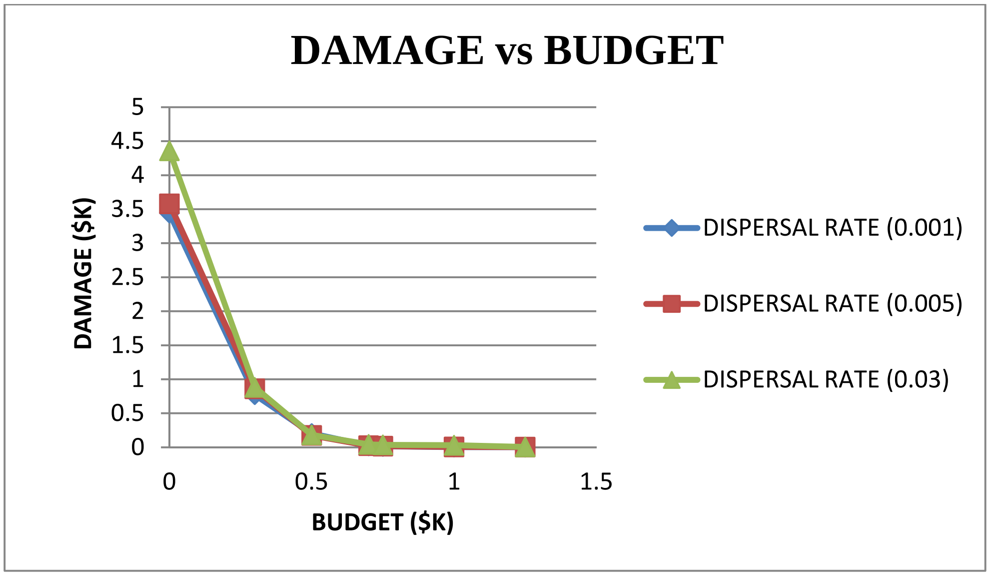

Figure 5.14 - Effect of Dispersal Rate on Damage over Budget with Low Initial Population

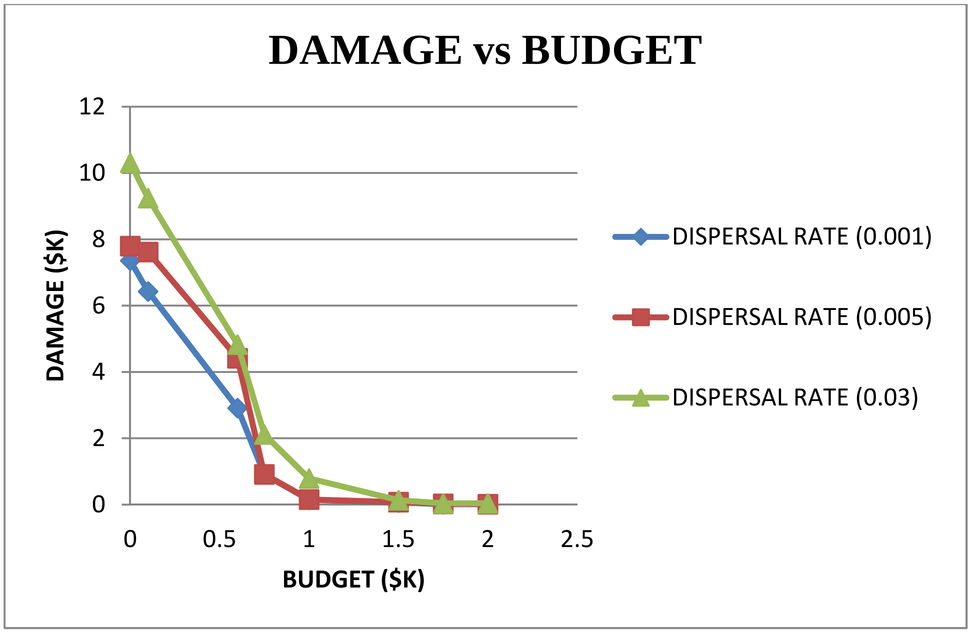

Figure 5.15 - Effect of Dispersal Rate on Damage over Budget with Medium Initial Population

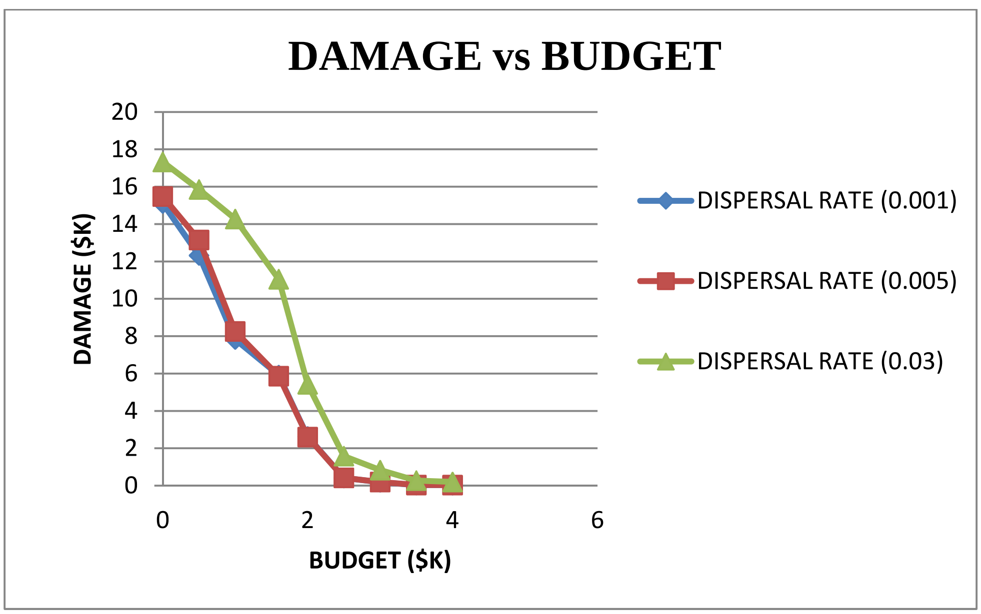

Figure 5.16 - Effect of Dispersal Rate on Damage over Budget with High Initial Population

4.6.5 Optimal Budget Allocation over Each Period of Time Interval for Different Initial Populations

In this experiment, the allocation of different budgets over each time period is determined for different initial populations based on the solution of the mathematical model provided in Chapter 3. Figures 5.17 to 5.20 show the budget allocation over each time period with respect to very tight, tight, moderate, and ample budgets for four different initial populations. The budget values are obtained from the first experiment based on the damage vs. budget levels. It can be seen that most of the budget is utilized in the first and second periods when the budget is tight and very tight. The maximum utilization of medium and ample budgets appears in the second and third periods. The model connotes that the very tight and tight budget should be utilized at maximum in the first and second periods of the time interval, irrespective of the initial population. The utilization of a moderate budget linearly decreases from period 1 to period 3 for very low, low, and medium initial populations. For a high initial population, the maximum utilization of a moderate budget is taken in first and second periods. The ample budget is utilized maximally in the third period. The utilization curve linearly increases as the period increases. This experiment will help landowners make decisions on budget amounts to be used over each time period of the planning time interval when controlling Sericea Lespedeza invasion with respect to different initial populations.

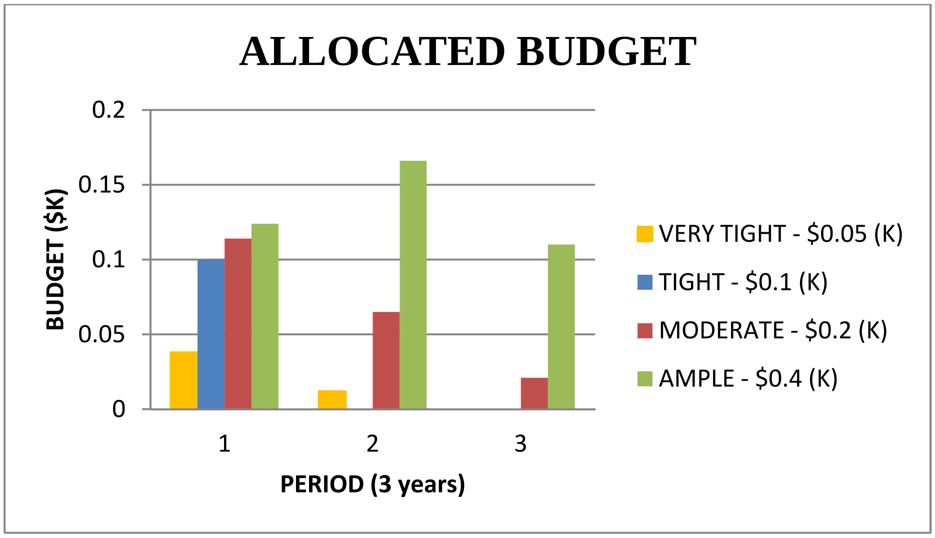

Figure 5.17 - Budget Allocation over Time Period with Very Low Initial Population

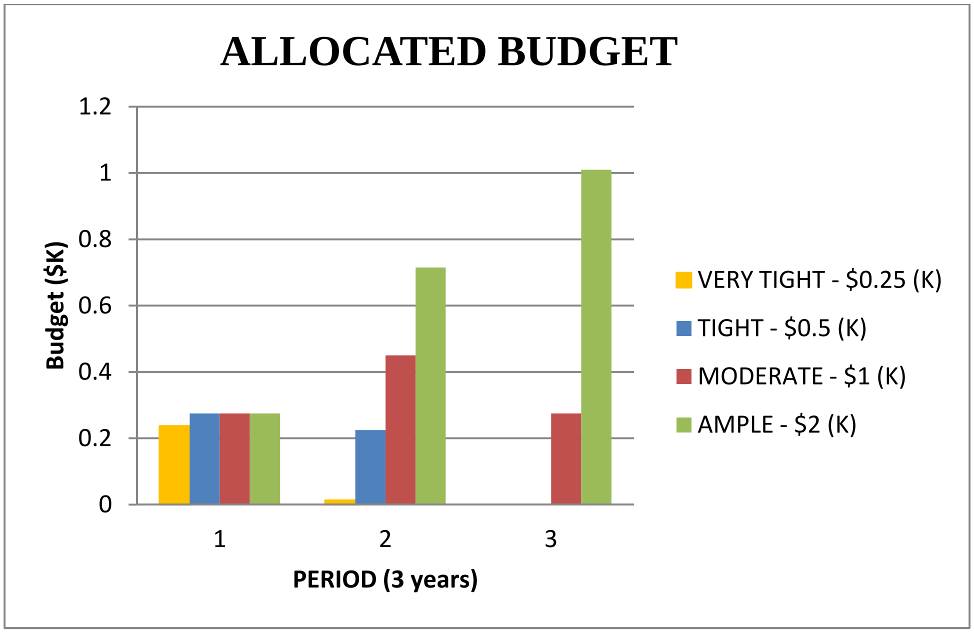

Figure 5.18 - Budget Allocation over Period with Low Initial Population

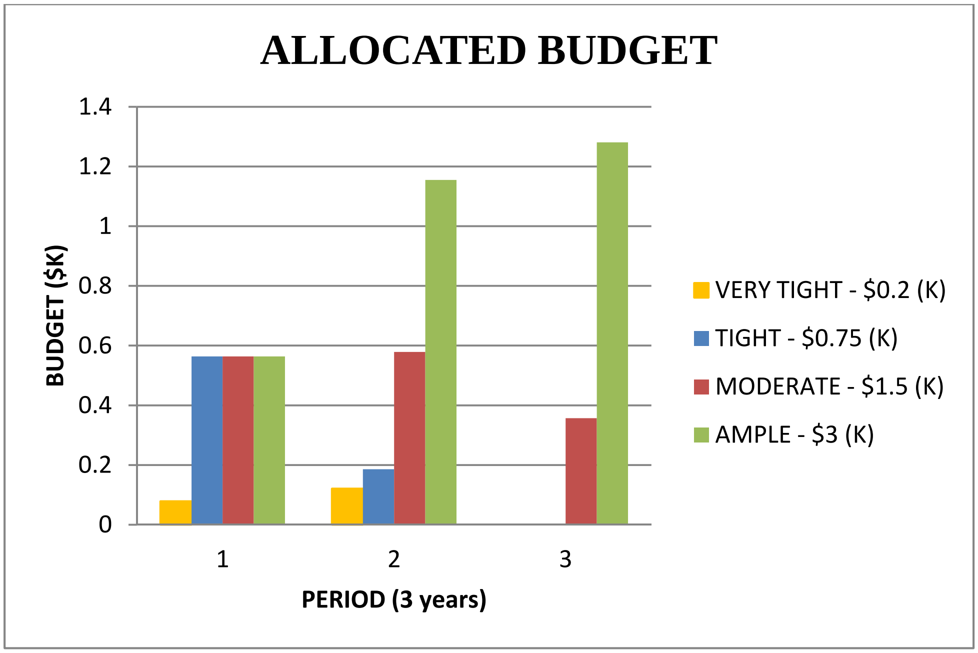

Figure 5.19 - Budget Allocation over Period with Medium Initial Population

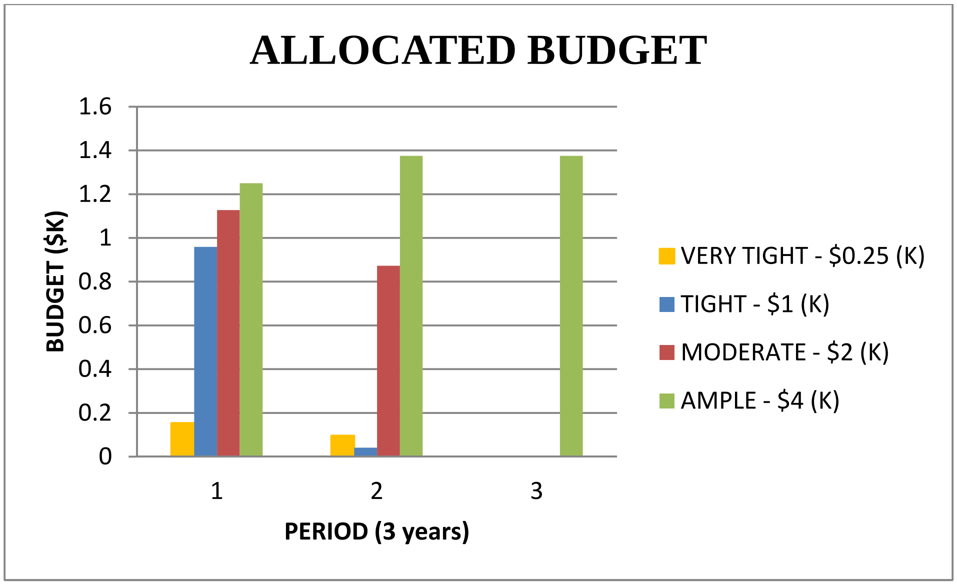

Figure 5.20 - Budget Allocation over Period with High Initial Population

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

5.1 Conclusions

In this research, a non-linear mixed-integer programming model was developed to provide economically efficient treatment strategies to control the invasion of Sericea Lespedeza in Kansas. The biological characteristics of Sericea Lespedeza and its economic damages were studied. The model minimizes the damage caused by Sericea Lespedeza subject to budget, population growth, seed bank, and carrying-capacity constraints. Data collection was done considering both economical and biological factors, and all data are converted to the scale of one acre of land. The model was coded in a mathematical programming language to obtain the results based on various management scenarios. However, the non-linearity of the model makes it difficult to provide results for the practical conditions. The model was linearized and the results were obtained accordingly.

Experiments were conducted by considering different parameters. Four different initial populations were considered based on the invasion area and the level of intensity. The first experiment was conducted to determine the optimal budget required to reduce the damage for different initial populations. The second experiment shows the effect of using herbicides with different kill rates. The third experiment shows yearly damage caused by Sericea Lespedeza. The fourth experiment shows the damage value for different dispersal rates. Finally, the model determines the budget required over each period for different initial populations. Results provide treatment strategies regarding when and where to apply herbicide treatments and the optimal budget to control Sericea Lespedeza.

5.2 Future Research

This research mainly focused on controlling the invasion of Sericea Lespedeza with the objective of minimizing revenue loss from hay and forage, while restricting the cost of treatment with a budget constraint for each period of the planning horizon. This research work will act as a basis for the following future work:

Multiple Objective Functions

This research could be extended by considering multiple objectives in the model. The current objective function focuses on controlling the economic loss. However, further research could be done by considering the ecological damages as well. Even though the plants are killed by herbicides, the seeds of Sericea Lespedeza are viable for a number of years. Therefore, the objective function could be modeled to minimize the population of seeds.

Seed Dispersal

The current research considers the grid model for seed dispersal. This model could be extended further to control the spread of Sericea Lespedeza by considering the dispersal through wind, animals and movement by human.

Growth

This research could also be further extended by comparing the deterministic and stochastic growth models. Each invasive species has its own germination rate and pattern of spreading. Environmental conditions, adaptability to soil, competence level against native species, and growth rates are factors to be considered in a stochastic model.

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