Integrated Bioeconomic Modeling of Invasive Species Management

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Three Approaches

Objectives of our Research:

(1) Compare three bioeconomic modeling approaches with economic and biological feedbacks:

- computable general equilibrium ecosystem models (GEEM)
- optimal control/STELLA modeling
- bioeconomic stochastic dynamic programming methods (SDP)

(2) Apply all three modeling approaches to case studies of invasive species in agriculture (e.g. leafy surge) to provide quantitative guidance for cost-effective investments in alternative strategies

Sub-Project 1: Lead investigators D. Finnoff & J. Tschirhart – U. of Wyoming

GEEM of plant communities subject to invasion

- Resource Ratio Theory (RRT) with Optimizing Individuals
- RRT
  - competition takes place between species
  - However, in a vegetative stand competition takes place between individuals & behavior of individuals ultimately determines competitive outcomes
- Plants behave with purpose and individual plants adopt strategies to acquire and make efficient use of limiting resources in order to grow and reproduce
- Purposeful, efficient and consistent behavior suggests that plants behave as if they are optimizers
- Optimization model of individual plant behavior yields many testable hypotheses

GEEM: Resource Ratio with Optimizing Individuals

- Individual plants are part of a multi-species vegetative stand
- Each plant behaves *as if* it maximizes fitness net energy income, channeled into reproduction.
- Plants max net energy by choosing an optimum level of photosynthetically active green biomass, given plant densities and the availability of resources.
  - Optimum green biomass balances the marginal gains from photosynthesis with the marginal losses to respiration
- Optimization takes place within a time period:
  - Fitness net energies attained determine transitions across periods
- Data on individual characteristics are more available than the lumped parameters
- Walker et al. (1999) suggest five plant characteristics to be used to describe ecosystem function: biomass, specific leaf area (SLA), longevity, height and leaf litter quality
  - We use the first three along with two respiration characteristics to capture the behavior of individuals and population dynamics.

GEEM: Resource Ratio with Optimizing Individuals

If individual characteristics are invariant (apart from responses to resource levels) main predictions of the RRT (Miller et al. 2005) can be obtained:

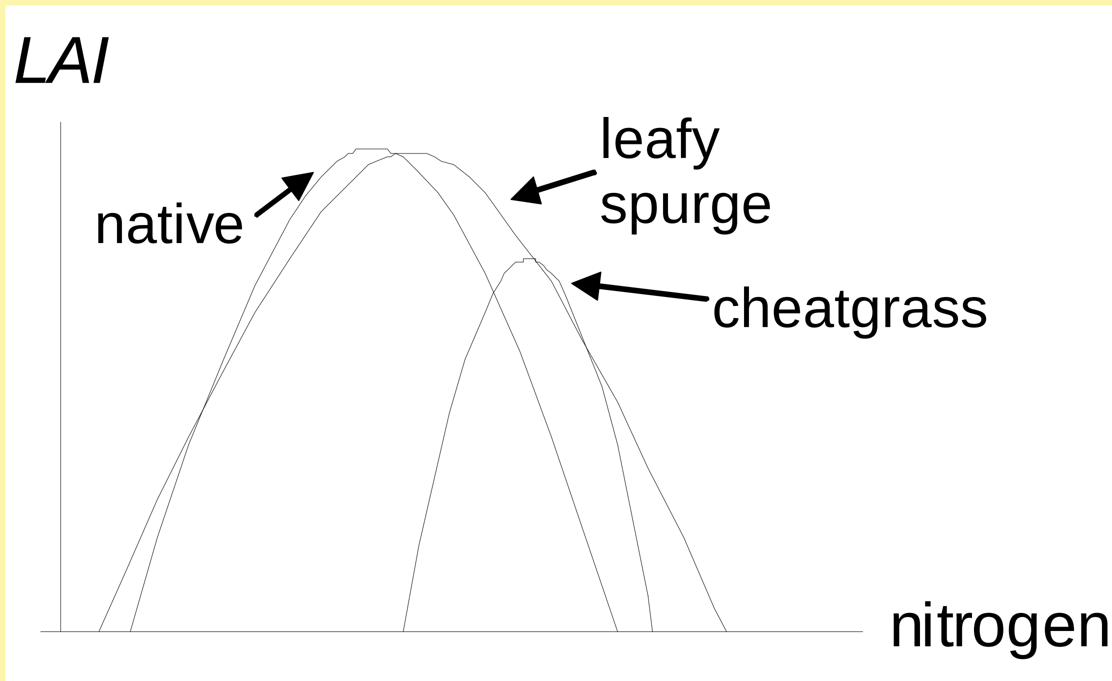
- Prediction 1 – The species that can survive at the lowest level of a resource is the best competitor for that resource
- Prediction 2 – Species dominance varies with the ratios of the availabilities of two resources
- Prediction 3 – The competitive exclusion principle: # of coexisting species is less than or equal to the number of resources
- Prediction 6 – Trade-offs in resource use must occur for species to coexist

Model also shows:

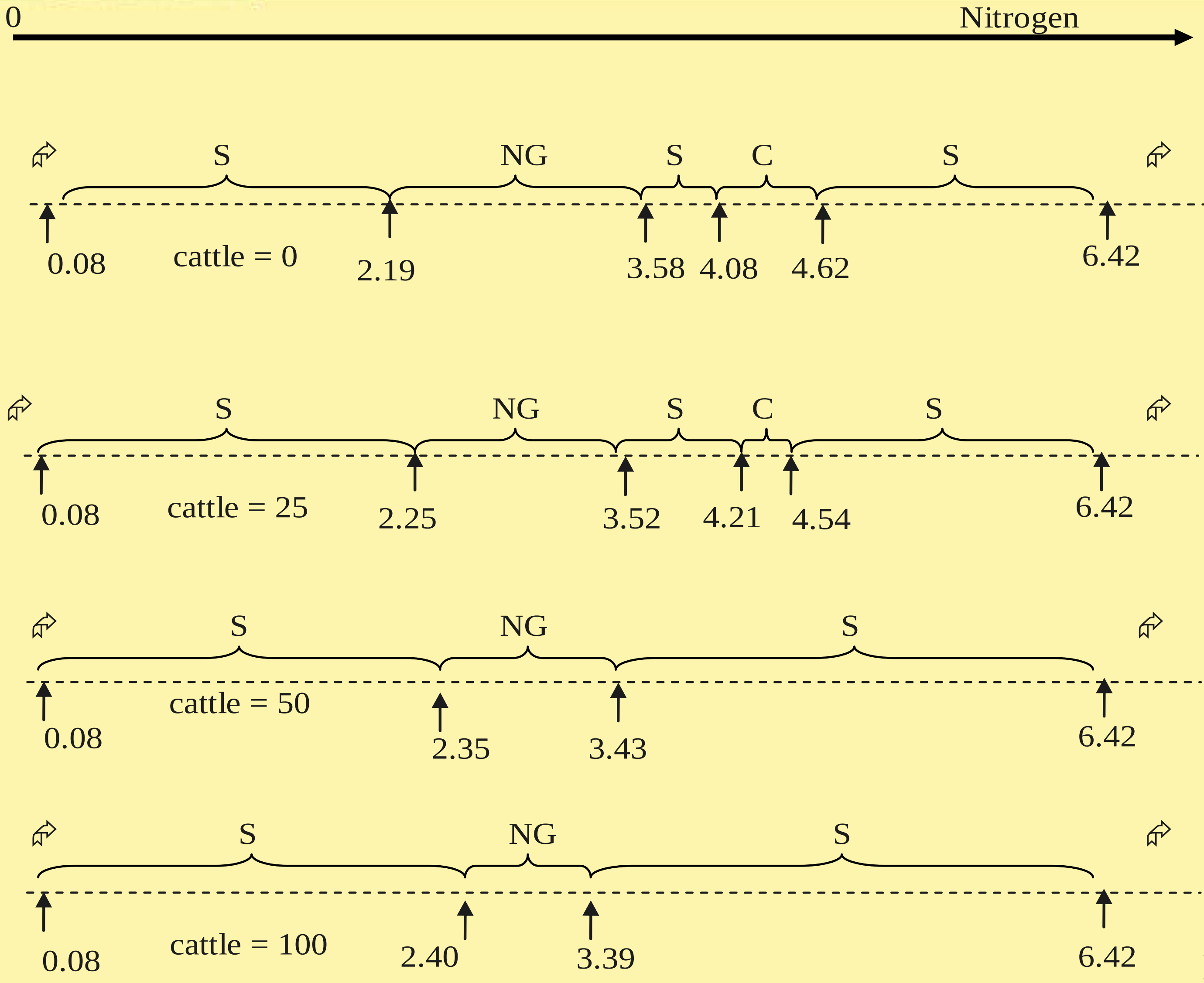
- Dominant species in low-resource sites more responsive to increased resources than dominant species in high-resource sites
- Species better suited to low nutrient levels are competitively eliminated at high nutrient levels & vice versa
- When individual characteristics differ across species, main predictions of the resource-ratio theory are not obtained:
  - e.g. number of coexisting species can exceed the number of resources…
  - when characteristics differ there are ecological distinctions between individuals which allow them to make adaptive changes so that species can coexist (Levin 1970).
- Optimization model yields numerous predictions about how different individual characteristics (e.g. SLAs) effect steady-state biomasses and populations
  - Also provides micro foundations for species level approaches!

GEEM Application: Stemming Aliens - Preventing the Spread of Multiple Invaders

- Perennials vs. Annuals
  - Buffalo Grass and Blue Grama
  - Cheat grass and Wheatgrass
- Grasses vs. Invasive Aliens
  - Leafy Spurge, Canada Thistle and Yellow Star Thistle
  - BLM estimates 14% growth rate
  - 56 million acres will be infested by 2010
  - $130 Million in annual losses in Wyoming, Dakotas and Montana



Stemming Aliens : SS Predictions of Community Composition



S = leafy spurge
NG = native grass
C = cheatgrass

Stemming Aliens - Preventing the Spread of Multiple Invaders

- Niche creation through grazing stress
- Species composition may be as important as total biomass
- Role of foresight in the speed of spread of invaders
  - Temporal externality causes an under “investment” in natural capital

Optimal Control Model

- Adapted from Pitafi and Roumasset (2004)
- Changes to Model

1. Benefit function is zero (no direct benefit of extracting invader)
2. Cost-min problem instead of Net Benefit-max problem
3. Only post-invasion (no reintroduction)

Optimal Control Model

$$\min_{LSeaten} \int_0^{\infty} (C(LS, LSeaten) + D(LS))e^{-rt}dt$$

$$s.t. \dot{LS} = g(LS) - LSeaten$$

$$LS(t=0) known$$

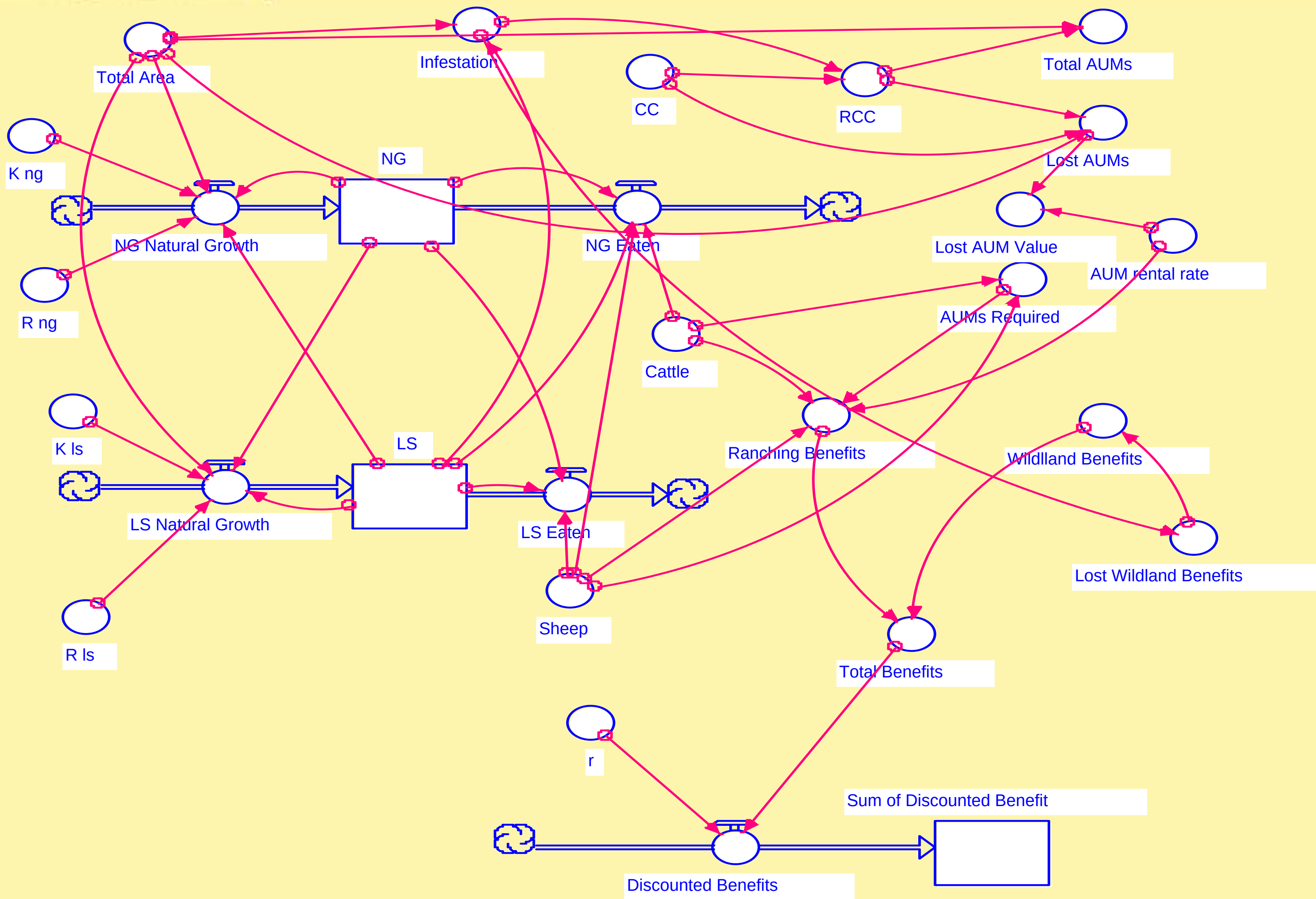
$$H = [-C(LS, LSeaten) - D(LS)] + \lambda[g(LS) - LSeaten]$$

$$\frac{dH}{dLSeaten} = -\frac{dC}{dLSeaten} - \lambda = 0$$

$$\frac{dH}{dLS} = [-\frac{dC}{dLS} - \frac{dD}{dLS}] + \lambda(\frac{dg}{dLS}) = r\lambda - \dot{\lambda}$$

$$\frac{dH}{d\lambda} = g(LS) - LSeaten = \dot{LS}$$

Stella Simulation Diagram



Results

- Resulting spread and associated damage from leafy spurge expansion more highly sensitive to sheep grazing than cattle grazing rates (up to 2000% larger change from proportional change in sheep grazing vs. cattle grazing)
- The increased sheep grazing in the Thunder Basin Grassland (almost 1-1 sheep-cattle ratio instead of 1-7 in 4-state area) is an important component in reducing the spread of leafy spurge

Optimal Control: Key Restrictions

- Unable to provide Net Benefit-max (cost-min instead) due to volatility in cattle/sheep price/profit (results depend entirely on price/profit chosen)
- Direct reduction in native grass productivity from leafy spurge expansion (Bangsund et al, 2000)

Optimal Control: Next Step in Research

- Provide optimal steady state stocking rate from optimal control model to compare to simulation results for current practices in area, 4-state average grazing practices, and simple rules of thumb practices

Sub-Project 3 : Lead Investigator Brian Leung – U. of McGill

- Integrating data, biological and decision models for invasive species management: Application to leafy spurge (*Euphorbia esula*)
  - Invasive species are costly ($137 billion for eradication and control in US
  - Better decisions needed about control strategies
  - Decision theory allows optimal decision given explicit criteria
  - Need to integrate population dynamics, spread, uncertainty, and temporal changes in management policies with decision theory
  - Stochastic dynamic programming (SDP) explicitly incorporates uncertainty, dynamic management decisions, forecasting and future optimal policies
  - We build a biological sub-model based on coupled-map lattices (CML model) to integrate leafy spurge growth, spread, time and uncertainty

SDP

- Methods
  - A density-dependent logistic growth equation for leafy spurge population dynamics
  - A coupled map lattices model (CML) modeled spread of leafy spurge
  - Field data used to parameterize the CML model using a grid-search algorithm
  - 3 control strategies: no control, biological control and herbicide control
  - Time horizon of 81 years
  - Costs of control strategies based on literature

SDP

- Results and Discussion
  - CML model fit the field data well
  - Optimal control strategy dependent on area, density and time horizon (Fig. 1)
  - Marginal gains and future welfares explained most patterns of optimal strategies
  - Dynamic control, forecasting and time horizons important to management programs (Fig. 2)
  - May consider Integrated Pest Management strategies and compare our results with different decision theory models

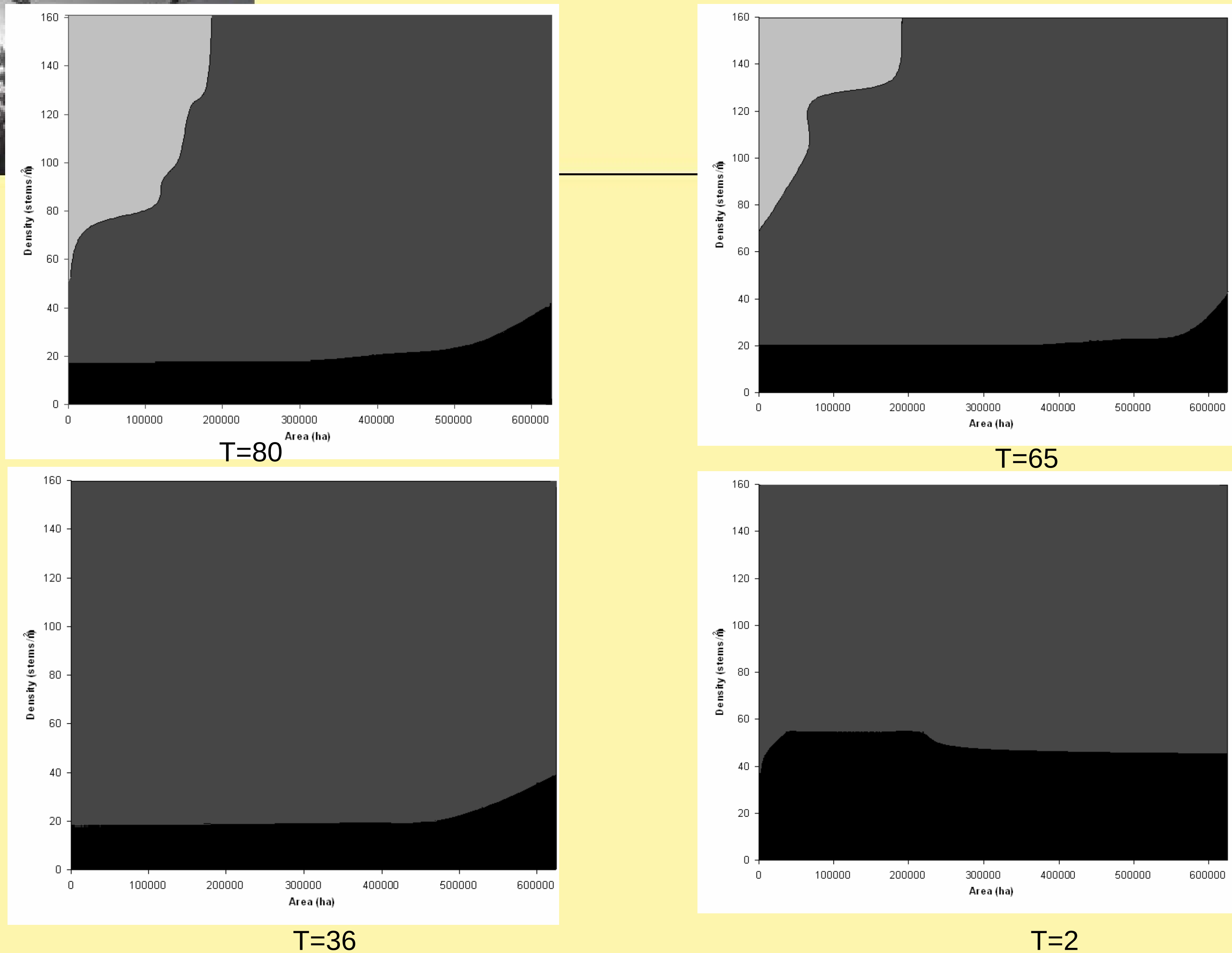
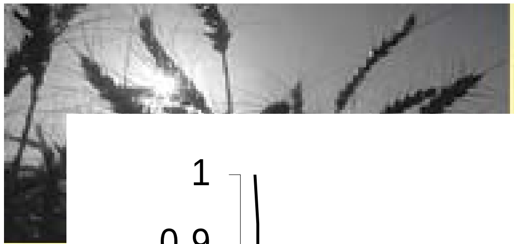


Figure 1. Optimal control strategy applied at a given year T for difference area (ha) of spread and density (stems/m2) of leafy spurge. Light grey= herbicide control, grey= bio-control and black= no control. T=80 years is the time horizon in the SDP model.



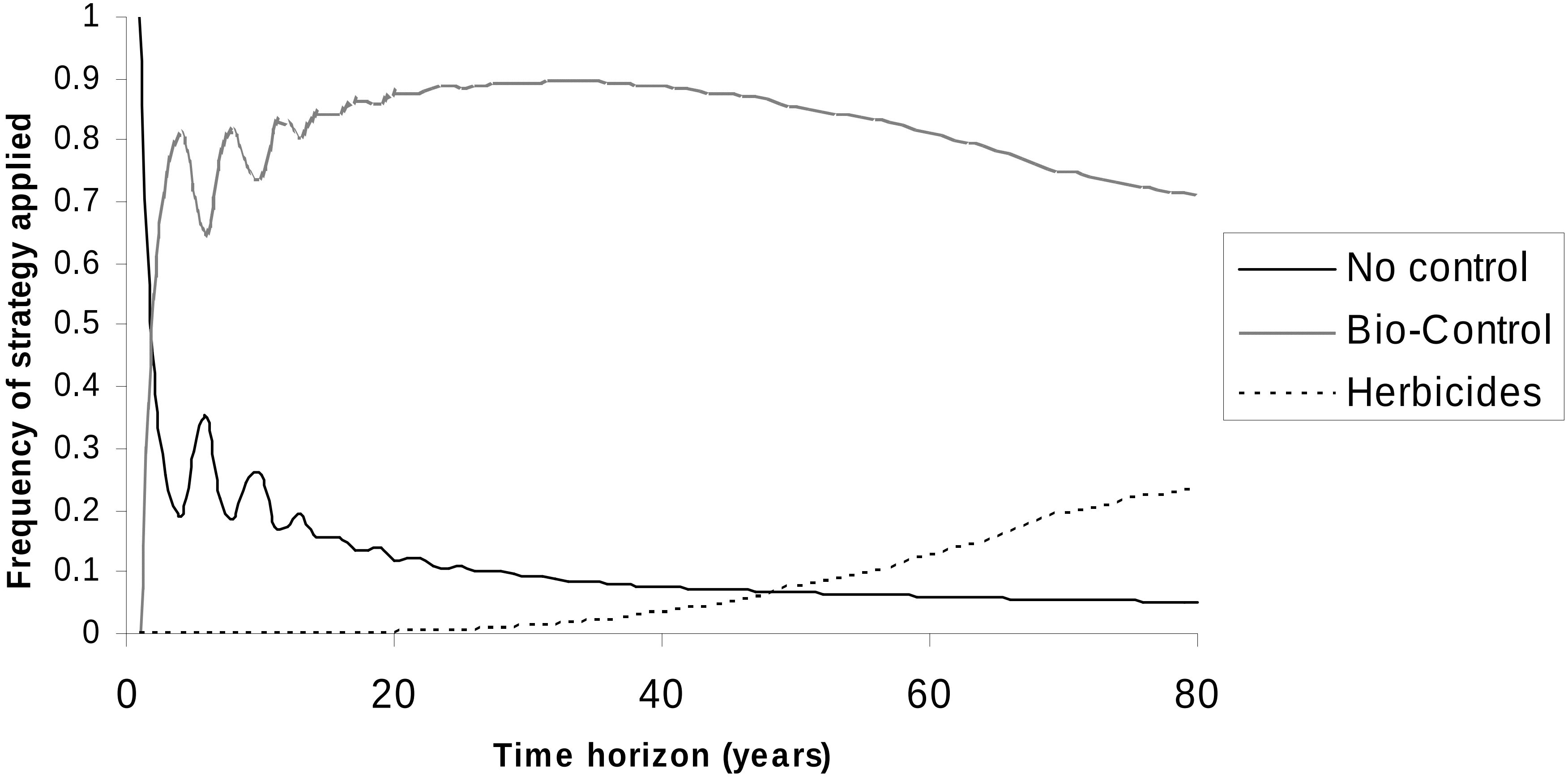


Figure 2. Frequency of the optimal strategy applied in each year to control leafy spurge.

Combined Future Work

- Compare and contrast approaches
- Define critical restrictions of each
- Define key insights of each
- Can we mesh the methods?