Optimal Forest Management for Interdependent Products:

A Nested Dynamic Bioeconomic Model

Tong Wu
Cornell University

C.-Y. Cynthia Lin Lawell
Cornell University

David R. Just
Cornell University

Jiancheng Zhao
Zhejiang Academy of Forestry

Zhangjun Fei
Boyce Thompson Institute and Cornell University

Qiang Wei
Nanjing Forestry University

Motivation

- Forests supply the world's population with timber and non-timber forest products.
- These include renewable products that can be harvested at more frequent intervals than the trees themselves.
  - Examples include fruits, nuts, and maple syrup

This Paper

- We develop a novel nested dynamic bioeconomic model of the management of forests that generate interdependent products that differ in their:
  - growth cycles
  - rates of growth
  - lengths of growing periods
  - potential harvest frequency

Application: Moso Bamboo Management

Moso bamboo (*Phyllostachys edulis*) is the single most important bamboo species in China.

Moso Bamboo Management

- Both bamboo stems and bamboo shoots are products that are sold on the market
- Winter shoots have a higher unit market price than spring shoots
- Involves making decisions about the timing and quantity of bamboo stem harvests and bamboo shoot harvests
- Optimal Moso bamboo management is a complex dynamic problem

Research Objectives

- Solve for the dynamically optimal bamboo stem and shoots harvesting strategies
- Compare the optimal Moso bamboo management strategy with the actual decisions being made by bamboo farmers
- Use our nested dynamic bioeconomic model to develop a dynamic structural econometric model to understand the beliefs and perceptions of bamboo farmers that underlie and rationalize their actual harvesting decisions as revealed in the data
- Simulate, analyze, and design policies and institutions to improve Moso bamboo forest management

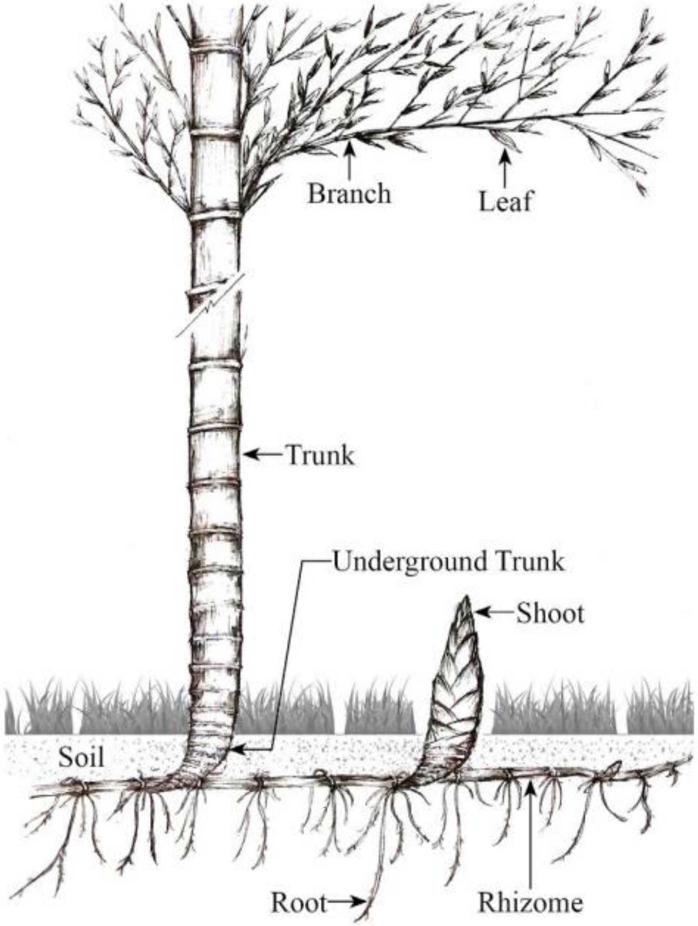
Agenda

- Introduction
- Dynamic Bioeconomic Model
- Numerical Results
- Optimal vs. Actual
- Dynamic Structural Econometric Model
- Conclusion and Next Steps

Agenda

- Introduction
- **Dynamic Bioeconomic Model**
- Numerical Results
- Optimal vs. Actual
- Dynamic Structural Econometric Model
- Conclusion and Next Steps

Dynamics and Interdependence of Bamboo Stem and Bamboo Shoots



Song, X., Peng, C., Zhou, G., Gu, H., Li, Q., & Zhang, C. (2016). Dynamic allocation and transfer of non-structural carbohydrates, a possible mechanism for the explosive growth of Moso bamboo (Phyllostachys heterocycla). *Scientific Reports*, *6*(1), Article 1.

- Bamboo shoots grow annually from a bamboo plant's underground rhizomes.
- Bamboo shoots only grow within a year.
  - Winter shooting and spring shooting
- Bamboo shoots grow into bamboo plants after the end of spring shooting.
- Bamboo stems continue to grow each year until age 4-5 years.
- The harvesting of bamboo stems entails cutting down the bamboo plant, while the harvesting of bamboo shoots does not.

Bamboo growth function

- We use a separate Chapman-Richards model for the biomass growth of each of the three types *j* of bamboo products:
  - winter shoots
  - spring shoots
  - bamboo stem

- The Chapman-Richards model is given by:

$$Y_j = A_j\left(1 - Q_j e^{-\alpha_j t_j}\right)^{1/(1-\mathrm{v_j})}$$

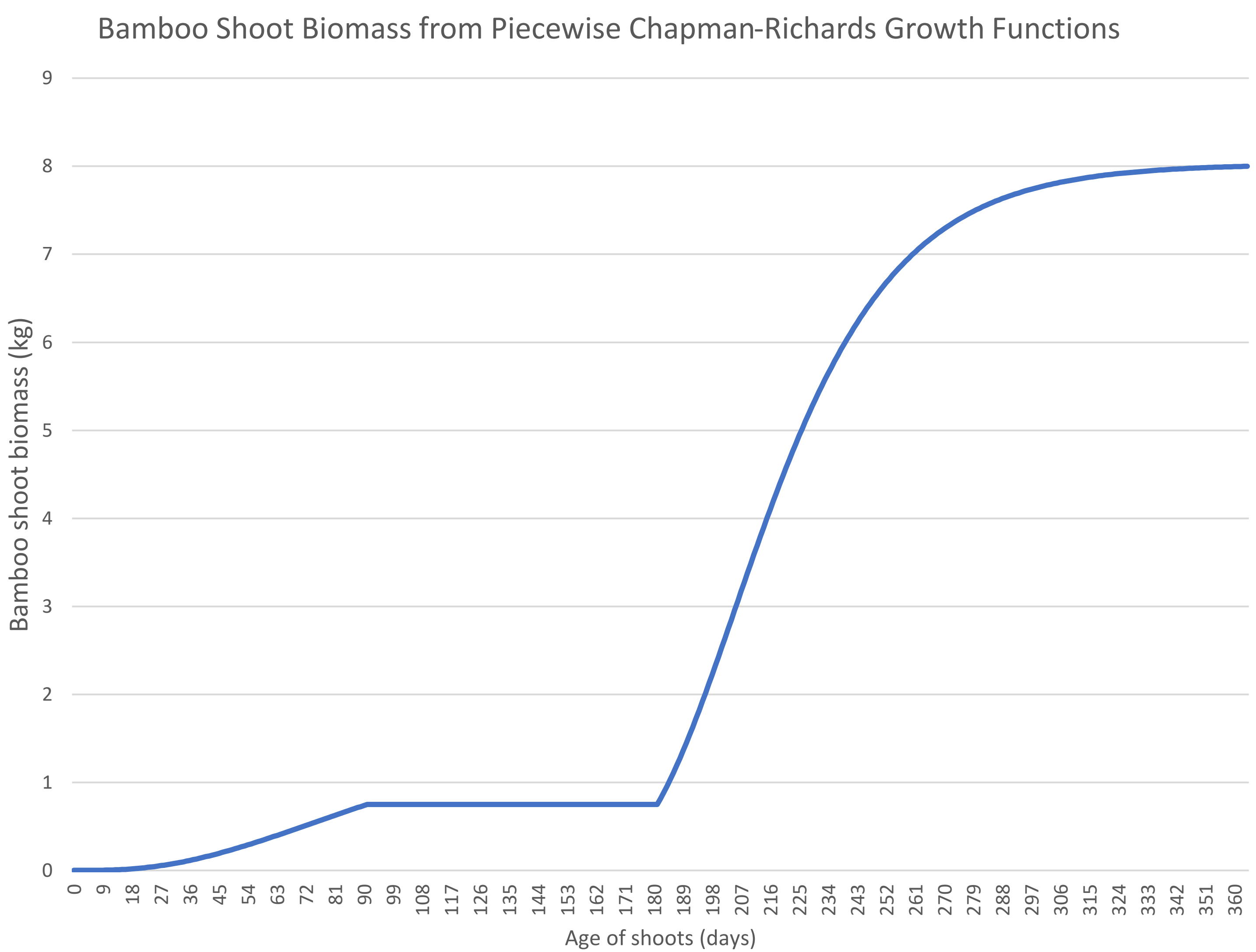
where:

  - Y_j is the total biomass for bamboo product *j* in a single bamboo plant

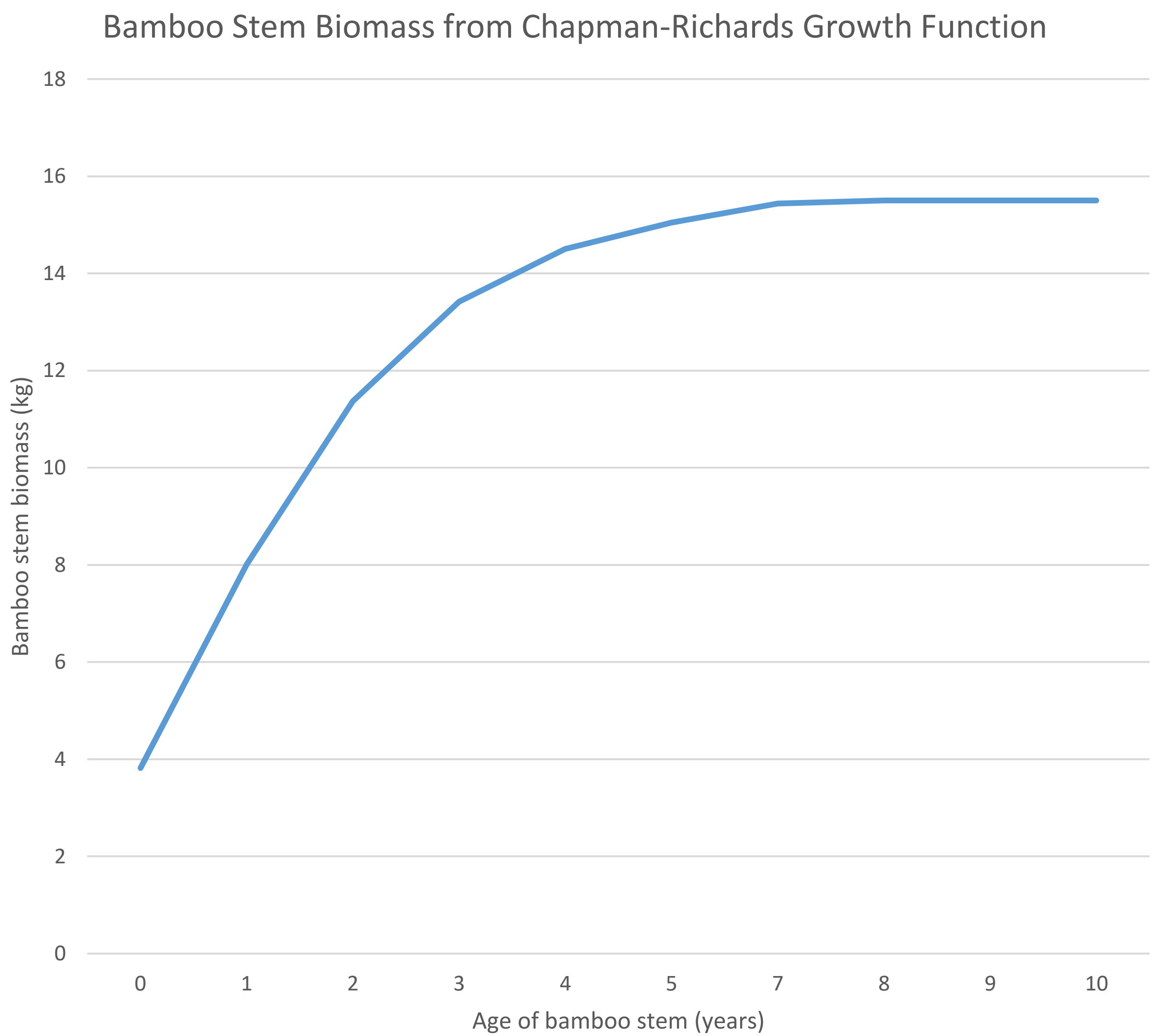
  - t_j is the age of bamboo product *j*

  - A_j, Q_j, α_j, v_j are parameters whose values we calibrate for each bamboo product *j*

Piecewise Chapman-Richards Growth Function for Bamboo Shoots



Chapman-Richards Growth Function for Bamboo Stem



Dynamic Model

- Numerical dynamic model nests an inner finite-horizon within-year daily dynamic programming problem within an outer finite-horizon between-year annual dynamic programming problem
    - The inner finite-horizon within-year daily dynamic programming problem captures daily bamboo shoot growth within a year
    - The outer finite-horizon between-year annual dynamic programming problem captures annual bamboo stem growth from year to year

- The control (action) variables are:
    - bamboo shoots harvest decision a_s
    - bamboo stem harvest decision a_b

- The value function, which is the present discounted value (PDV) of the entire stream of per-period payoffs when the bamboo shoot harvest and bamboo stem harvest decisions are chosen optimally, is given by the following Bellman equation:

$$V(s,d,y) = \max_{a_s,a_b} \underbrace{\pi(a_s,a_b,s)}_{\text{today's per-period payoff}} + \underbrace{\beta E[V(s',d',y')|s,a_s,a_b,d,y]}_{\text{continuation value}}$$

Sources of Uncertainty

- Allow rain to be stochastic

- There is a positive correlation between the number of bamboo shoots per hectare at the beginning of winter shooting in September, with precipitation during the preceding months of July and August

Sources of Uncertainty

- Allow rain to be stochastic

- There is a positive correlation between the number of bamboo shoots per hectare at the beginning of winter shooting in September, with precipitation during the preceding months of July and August

- Also allow daily shoots price to be stochastic
  - Use empirical distribution of daily winter shoots price and empirical distribution of daily spring shoots price

Agenda

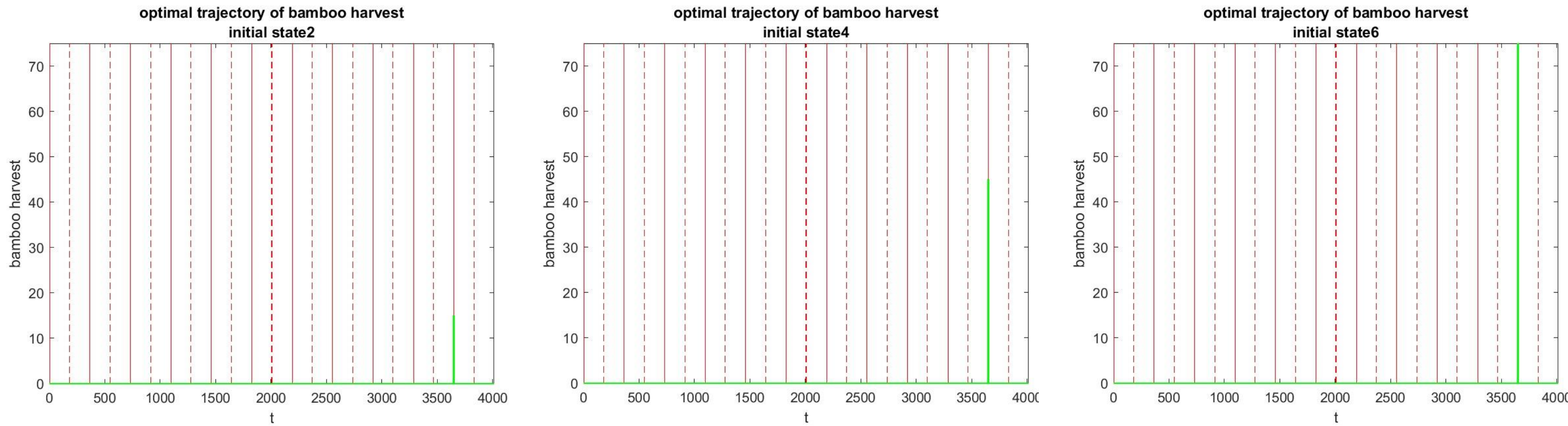
- Introduction
- Dynamic Bioeconomic Model
- **Numerical Results**
- Optimal vs. Actual
- Dynamic Structural Econometric Model
- Conclusion and Next Steps

Result #1:
Optimal Bamboo Stem Harvest

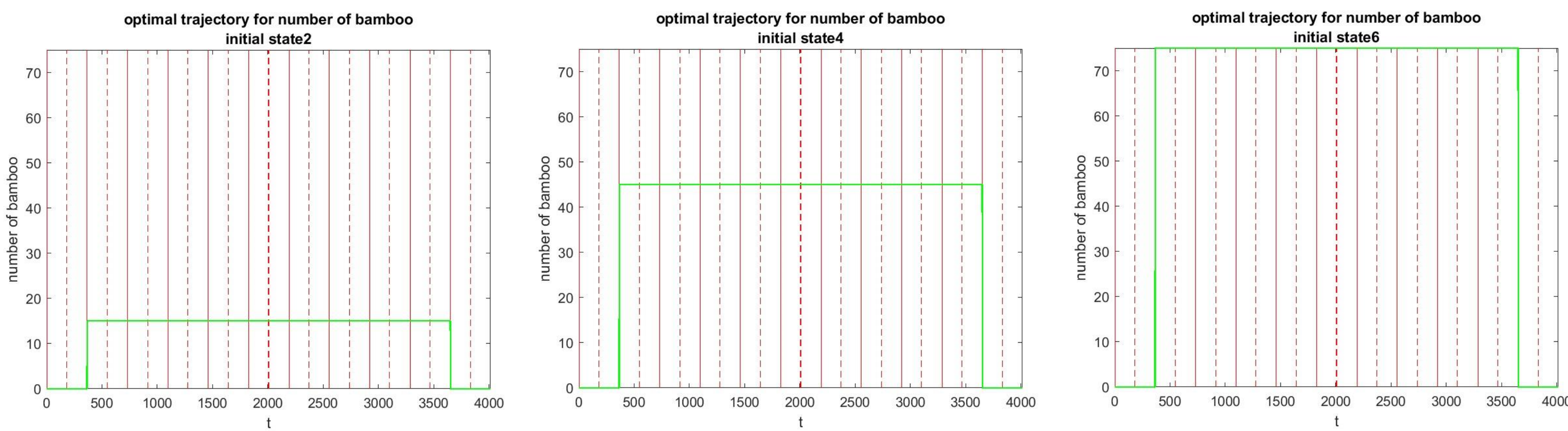
- Generally optimal to wait to harvest any bamboo stem until the 3rd year or later, after their growth has begun to slow down, and harvest bamboo stem at the beginning of the year

Optimal trajectories for bamboo stem harvest and number of bamboo stem over 11 years

Bamboo stem harvest



Number of bamboo stem



Optimal Bamboo Stem Harvest: Intuition

Why wait until 3rd year or later to harvest any bamboo stem?

- Allows bamboo stem biomass to accumulate
- Makes bamboo shoots harvest possible for multiple years
- Bamboo stem continues to grow each year until age 4-5 years

  => Bamboo stem growth begins to slow down around the end of the 3rd year and beginning of the 4th year

Optimal Bamboo Stem Harvest: Intuition

Why harvest bamboo stem at beginning of the bamboo growth year it is being harvested?

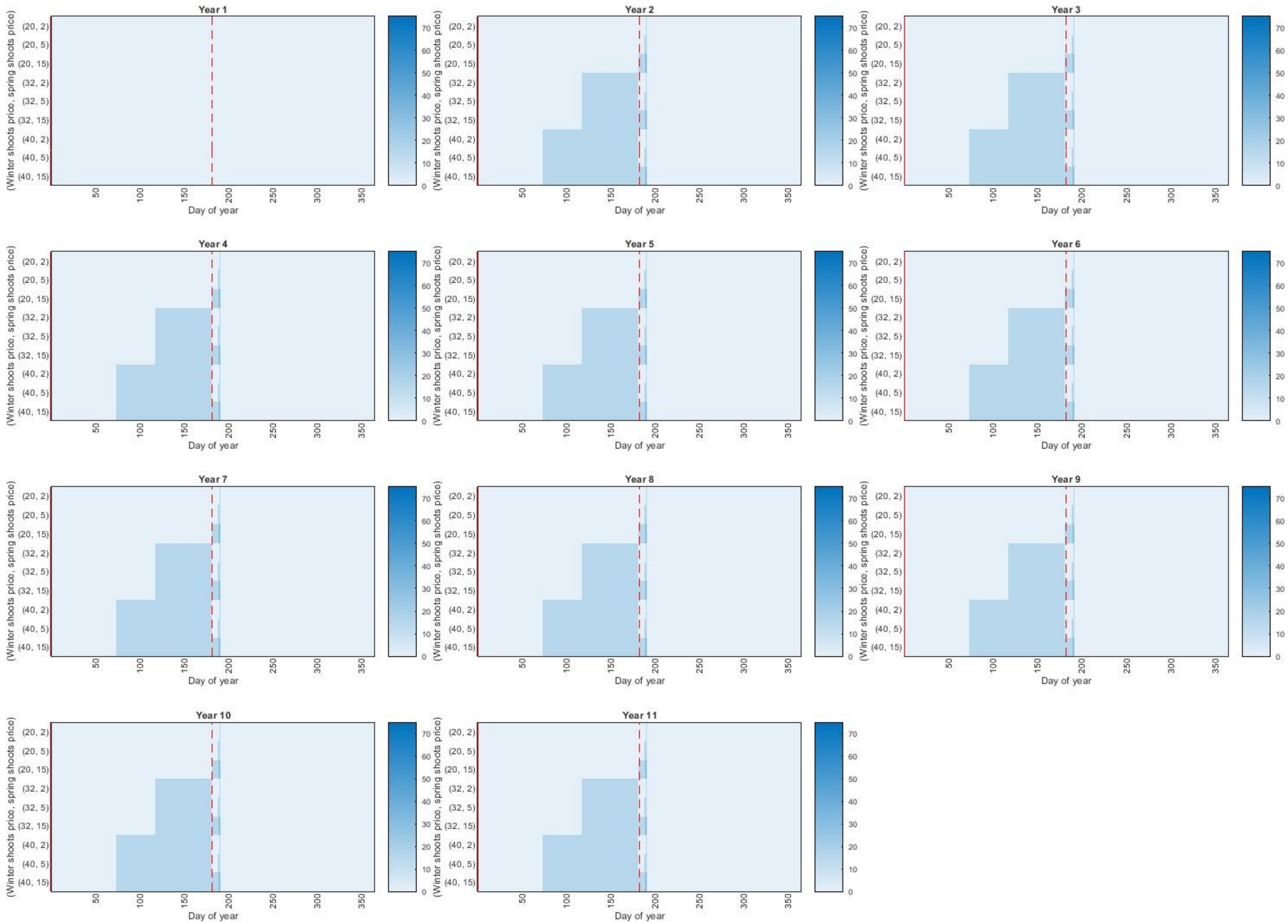
- The number of bamboo shoots at the beginning of each year depends on the number of bamboo stem remaining at the beginning of each year

- After bamboo stem growth has slowed down, any increase in bamboo stem biomass from delaying bamboo stem harvest past the beginning of the year will be small

Result #2:
Optimal Bamboo Shoot Harvest

- Generally optimal to harvest bamboo shoots each year that there are bamboo shoots, starting from the 2nd bamboo growth year
  - Should wait at least until mid-November and when winter shoots price is high to do any winter shoots harvest
  - Unless spring shoots price is high, should wait until last days of spring shooting for which spring shoots are marketable to do any spring shoots harvest

Daily bamboo shoots policy function over 11 years



Optimal Bamboo Shoot Harvest: Intuition

Why wait to 2nd year to harvest bamboo shoots?

- In the 1st year, bamboo shoots grow into bamboo stem at the end of the year
- If bamboo shoots are left to grow into bamboo stem at the end of the 1st year, then there would be both bamboo shoots and bamboo stem at the beginning of the 2nd year

Optimal Bamboo Shoot Harvest: Intuition

Why harvest bamboo shoots each year (starting from 2nd year)?

- Number of bamboo shoots at the beginning of each year is not affected by the bamboo shoot harvest in the previous year
    - Depends instead on number of bamboo stem remaining at the beginning of each year (starting from 2nd year)

Optimal Bamboo Shoot Harvest: Intuition

Why wait at least until mid-November and when winter shoots price is high to do any winter shoots harvest?

- Over 50% of winter shoots growth takes place during November
- Winter shoots growth stops at beginning of December
- After at least mid-November, should harvest winter shoots when the winter shoots price is high enough

Optimal Bamboo Shoot Harvest: Intuition

Why wait until last days of spring shooting for which spring shoots are marketable to do any spring shoots harvest unless the spring shoots price is high?

- The more the spring shoots grow, the more biomass

Optimal Policy: Summary

- Harvest all shoots each year that there are bamboo shoots, starting from the 2nd bamboo growth year
  - Allow shoots to grow as much as possible before each year's harvest
  - Harvest when shoots prices are high

- Wait until the 3rd or later bamboo growth years to harvest bamboo stem
  - After their growth has begun to slow down

- Harvest bamboo stem at the beginning of the bamboo growth year

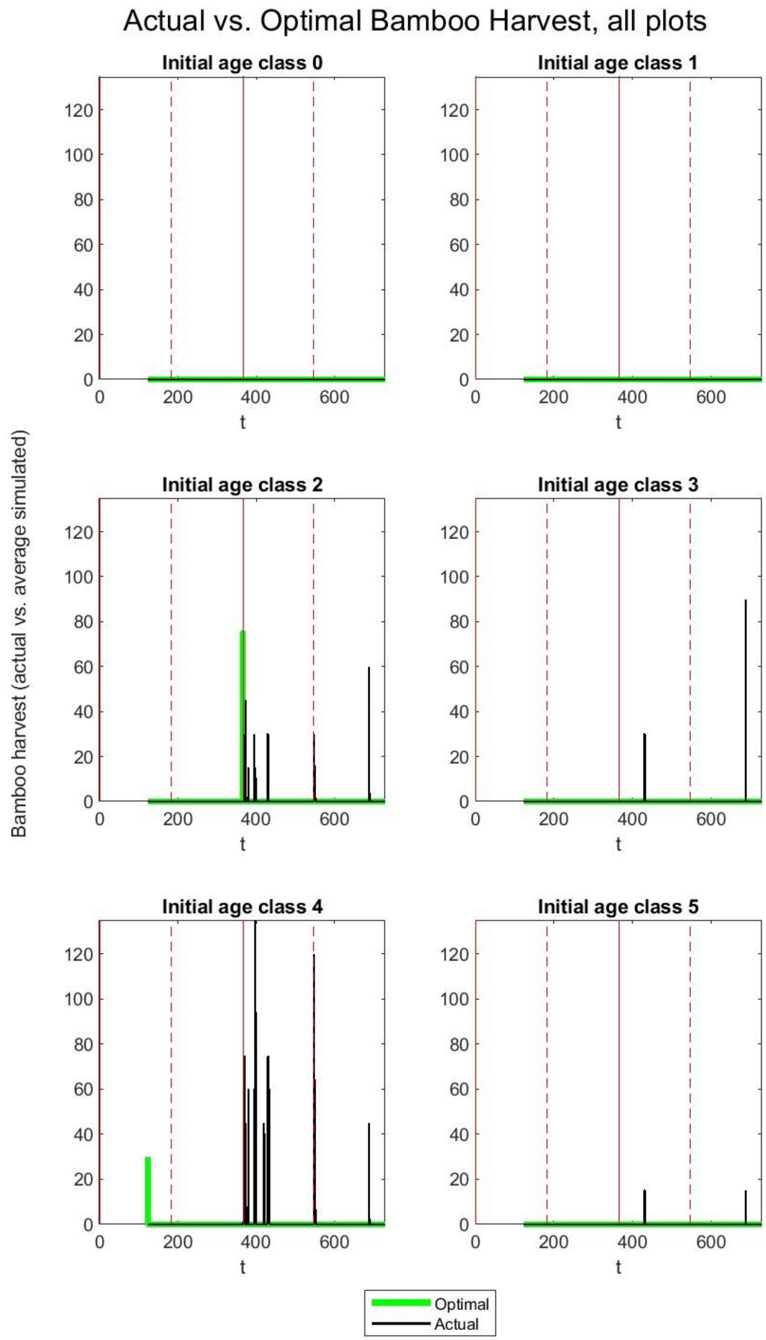
Agenda

- Introduction
- Dynamic Bioeconomic Model
- Numerical Results
- **Optimal vs. Actual**
- Dynamic Structural Econometric Model
- Conclusion and Next Steps

Comparing Optimal with Actual

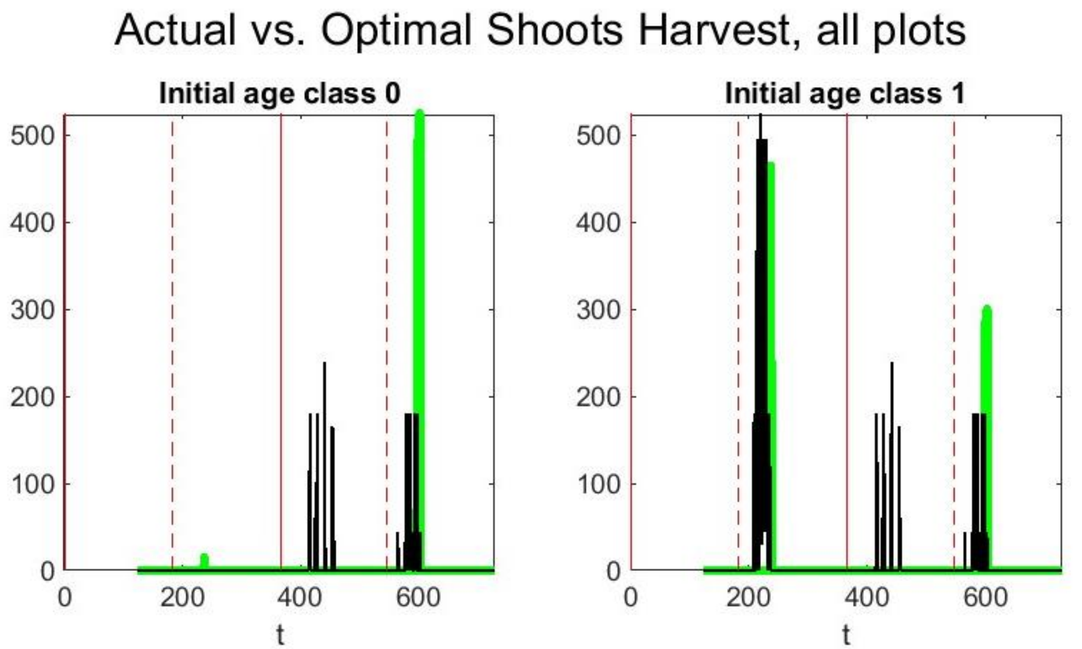
- We compare the optimal bamboo stem harvest and bamboo shoot harvest policy as given by our numerical dynamic model with actual data on bamboo shoot and bamboo stem harvests on multiple bamboo plots in multiple townships in Zhejiang province in China

- We also compare the optimal and actual welfare



Actual bamboo stem harvests tend to be close to what our model stipulates to be optimal

Bamboo stem harvests don't take place until age 3 or later



Actual spring shoots harvests tend to be consistent with what our model deems to be optimal

Actual winter shoots harvest took place in the data as early as mid-October when the winter shoots price was high.

But, across a wide range of parameters (including extremely low winter shoots cost or high discount rates), our model never found it optimal to harvest winter shoots that early despite the higher winter shoots price.

Actual vs. Optimal Harvests

- Actual bamboo stem and bamboo shoot harvests come close to approximating the optimal strategy, but have some features that differ from what our model suggests to be optimal.
- To the extent that some of these differences reflect possible sub-optimal behavior on the part of Moso bamboo forest managers, our results have important implications for ways to improve Moso bamboo forest management and policy.

Agenda

- Introduction
- Dynamic Bioeconomic Model
- Numerical Results
- Optimal vs. Actual
- **Dynamic Structural Econometric Model**
- Conclusion and Next Steps

Dynamic Structural Econometric Model

- To understand the beliefs and perceptions of bamboo farmers that underlie and rationalize their bamboo shoot and bamboo stem harvesting decisions as revealed in the data, we use our nested dynamic bioeconomic model to develop a dynamic structural econometric model adapted from Rust (1987)

Econometric Estimation

- We use maximum likelihood estimation to find the parameters θ to maximize the likelihood function:

$$L(\theta) = \sum_i \sum_d \sum_y \Pr(a_{idy} \mid s_{idy}, d, y; \theta)$$

- At each evaluation of the likelihood function, we solve for the continuation values and choice probabilities for each day *d* in each year *y*
- To solve for the continuation values and choice probabilities, we nest an inner finite-horizon within-year daily dynamic programming problem within an outer finite-horizon between-year annual dynamic programming problem

Agenda

- Introduction
- Dynamic Bioeconomic Model
- Numerical Results
- Optimal vs. Actual
- Dynamic Structural Econometric Model
- **Conclusion and Next Steps**

Ongoing and Next Steps

- Develop theory model
- Refine our comparison of the actual harvesting decisions with the optimal harvesting decisions
- Re-calculate actual welfare, optimal welfare, and the DWL from bamboo farmers' sub-optimal decision-making after making the improvements and refinements above
- Continue to develop and estimate our dynamic structural economic model

Features that are at least partially captured by some specifications of our model

- Winter shoots growth
- Variation in bamboo shoot price and bamboo stem price over time
  - We allow for shoots prices to be stochastic
  - In structural model, we are using actual daily bamboo shoots prices and bamboo stem prices
- Capacity and/or labor constraints on the amount that is feasible to harvest in one day
  - We allow for possible convex costs in bamboo shoots harvest

Ongoing and Next Steps

- Continue to develop and estimate our dynamic structural economic model to estimate the parameters econometrically and capture several additional features, including:
  - Effects of bamboo stem and bamboo shoot harvests on bamboo stem and bamboo shoot price
  - Liquidity constraints during the season that may lead bamboo managers to harvest some bamboo shoots or bamboo stem early
  - Carbon sequestration motives
  - Alternative crops or uses of the land
  - Environmental benefits of bamboo forest
- Simulate the effects of various alternative forest conservation policies and forest management approaches on bamboo shoot harvest, bamboo stem harvest, forest conservation, and welfare.
- Design sustainable and effective forest management policies that maximize net benefits to society.

Conclusion

- Our results have important implications for Moso bamboo forest management in particular, and forest management more generally.

- Our novel nested dynamic bioeconomic model has important implications for the sustainable management of forests worldwide, particularly when the forests produce products that grow on trees, are renewable, and can be harvested at more frequent intervals than the trees themselves.
  - Examples include fruits, nuts, sap, and maple syrup.

Thank you!

Tong Wu
Cornell University
tw494@cornell.edu

Extra Slides

Issues Faced by Chinese Bamboo Forests

- The bamboo stem price has decreased significantly in recent years with a higher labor cost, and some bamboo plants have been left unharvested when matured
- In contrast, winter shoots have sometimes been over-harvested for high profit, leaving too few shoots for future bamboo forest development
- Current bamboo forest management strategies may be inefficient and unsustainable, leading to:
  - profit loss
  - deadweight loss
  - deterioration of the bamboo forest resource

Dynamic Structural Econometric Model

- To understand the beliefs and perceptions of bamboo farmers that underlie and rationalize their bamboo shoot and bamboo stem harvesting decisions as revealed in the data, we use our nested dynamic bioeconomic model to develop a dynamic structural econometric model adapted from Rust (1987)
- Our dynamic structural econometric model builds upon our numerical bioeconomic model, and additionally accounts for unobservable state variables that bamboo farmers observe (but we do not observe) when they make their bamboo shoot and bamboo stem harvesting decisions

Dynamic Structural Econometric Model

- Value function incorporating unobserved shocks $\epsilon(a)$:

$$V(s,d,y;\theta) = \max_{a=(a_b,a_s)} \pi_0(s,a,d,y;\theta) + \varepsilon(a) + \beta E[V(s',d',y';\theta) \mid s,a,d,y]$$

- Continuation value:

$$V^c(s,a,d,y;\theta) = E[V(s',d',y';\theta) \mid s,a,d,y]$$

- Choice probabilities:

$$\Pr(a \mid s,d,y;\theta) = \frac{\exp(\pi_0(s,a,d,y;\theta) + \beta V^c(s,a,d,y;\theta))}{\sum_{\tilde{a}} \exp(\pi_0(s,\tilde{a},d,y;\theta) + \beta V^c(s,\tilde{a},d,y;\theta))}$$

Econometric Estimation

- We use maximum likelihood estimation to find the parameters θ to maximize the likelihood function:

$$L(\theta) = \sum_i \sum_d \sum_y \Pr(a_{idy} \mid s_{idy}, d, y; \theta)$$

- At each evaluation of the likelihood function, we solve for the continuation values and choice probabilities for each day *d* in each year *y*
- To solve for the continuation values and choice probabilities, we nest an inner finite-horizon within-year daily dynamic programming problem within an outer finite-horizon between-year annual dynamic programming problem