Optimal Forest Management Under Uncertainty: A Framework for Stochastic Dynamic Bioeconomic Modeling[1,2]

Tong Wu,
David R. Just, C.-Y. Cynthia Lin Lawell, Jiancheng Zhao,
Zhangjun Fei, Ariel Ortiz-Bobea, Qiang Wei

Abstract

Sustainable forest management is an important issue worldwide. Forests supply the world's population with timber and non-timber forest products, including renewable products such as fruits, nuts, and maple syrup that can be harvested at more frequent intervals than the trees themselves. In this paper, we review, synthesize, and discuss the literature on forest economics and management; review our research that develops a nested dynamic bioeconomic model of the management of forests that generate interdependent products; and present a framework for stochastic dynamic bioeconomic modeling of optimal forest management under uncertainty. Our research and framework have important implications for the sustainable management of forests worldwide.

---

[1] Wu: Cornell University; tw494@cornell.edu. Just: Cornell University; drj3@cornell.edu. Lin Lawell: Cornell University; clinlawell@cornell.edu. Zhao: Zhejiang Academy of Forestry; jiancheng68@163.com. Fei: Boyce Thompson Institute and Cornell University; zf25@cornell.edu. Ortiz-Bobea: Cornell University; ao332@cornell.edu. Wei: Nanjing Forestry University; weiqiang@njfu.edu.cn.

[2] We thank Ryan Abman, H. Jo Albers, Jeff Arnold, Trevor Arnold, Joe Balagtas, Rachid Belhachemi. Susanna Berkouwer, Léa Bou Sleiman, Jacob Bradt, Daniel Brent, Mike Buffo, Marshall Burke, Jonah Busch, Virginia Callison, Luming Chen, Lauren Chenarides, Sahan Dissanayake, Ida Djenontin, Jackson Dorsey, Molly Doruska, Luc Esprabens, Paul Ferraro, Scott Francisco, Stephie Fried, Teevrat Garg, Todd Gerarden, Dalia Ghanem, Tengda Gong, Gautam Gowrisankaran, Logan Hamilton, Ted Helvoigt, Danae Hernández-Cortés, Jerzy Jaromczyk, Valerie Karplus, Jim Kiniry, Cathy Kling, Samuel Kortum, Elena Krasovskaia, Yusuke Kuwayama, Ashley Langer, Jim Lassoie, David R. Lee, David Lewis, Dingyi Li, Shanjun Li, Mengwei Lin, Clark Lundberg, Erin Mansur, Toni Marcheva, Shana McDermott, Brandon McFadden, Michael Meneses, Carlos Muñoz Brenes, Anjali Narang, Ishan Nath, Matias Navarro Sudy, Harry Nelson, José Nuño, Frederick Nyanzu, David Popp, Linda Powell, Carson Reeling, Brigitte Roth Tran, Ivan Rudik, Michelle Segovia, Jonathan Scott, Chris Severen, Jeff Shrader, Shuyang Si, Peter Smallidge, Aaron Smith, Charlie Smith, Christophe Spaenjers, Nick Tsivanidis, Calum Turvey, Wayne Walker, David Weinstein, Matthew Wibbenmeyer, Peter Woodbury, Weiguang Wu, Tianming Yen, Shuo Yu, and Hui Zhou for detailed and helpful comments. We also benefited from comments from seminar participants at Cornell University; and conference participants at the 2024 International Business Analytics Conference (IBAC); the Western Forest Economists (WFE) Annual Meeting; the Northeastern Agricultural and Resource Economics Association (NAREA) Annual Meeting; an Association of Environmental and Resource Economists (AERE) session at the Western Economic Association International (WEAI) Annual Conference; the Agricultural and Applied Economics Association (AAEA) Annual Meeting; the University of Michigan conference on Forests & Livelihoods: Assessment, Research, and Engagement (FLARE). We thank Qin Li, Lina Liu, Jianping Pan, and Boqing Yuan for helping us with the data collection; for providing us information about bamboo management; and for helping to host our visits to the Zhejiang Provincial Key Laboratory of Bamboo of Zhejiang Provincial Academy of Forestry, the Anji Forestry Technology Promotion Center, the Fumin Bamboo Shoot Specialized Cooperative, and the Tianlin Bamboo Shoot Specialized Cooperative, respectively. We thank Jianyang Lin, the Party Secretary for Xikou Forest Farm in Longyou County, for his exceptional support and organization for our interviews and short trips to the trade corporation in Longyou County. This research was supported by Cornell Center for Social Sciences Cloud Computing Solutions, and was conducted with support from the Cornell University Center for Advanced Computing. We received funding for our research from the USDA National Institute of Food and Agriculture (NIFA); a Cornell TREESPEAR Research Grant; and a Cornell University Graduate School Conference Grant. Our IRB protocol (Protocol Number: IRB0148123) was granted exemption from IRB review according to Cornell IRB policy and under the Department of Health and Human Services Code of Federal Regulations 45CFR46.104(d). Just, Lin Lawell, and Ortiz-Bobea are Faculty Fellows at the Cornell Atkinson Center for Sustainability. All errors are our own.

1. Introduction

The sustainable management of forests is a critical, timely, and important issue worldwide. Forests supply the world's population with timber as well as renewable non-timber forest products such as fruits, nuts, and maple syrup that can be harvested at more frequent intervals than the trees themselves. Unfortunately, the extent of the world's forests continues to decline as human populations continue to grow and the demand for food and land increases (FAO, 2005; Matthews, 2012; FAO, 2015).

Owing to intertwined feedback links between biological and economic systems, bioeconomic modeling is challenging, and there is a considerable need for studies that couple economic models of decision-making with biophysical models to provide policy-relevant implications (Kling et al., 2017). In this paper, we review, synthesize, and discuss the literature on forest economics and management; review our research in Wu et al. (2024) that develops a nested dynamic bioeconomic model of the management of forests that generate interdependent products; and present a framework for stochastic dynamic bioeconomic modeling of optimal forest management under uncertainty. Our research and framework have important implications for the sustainable management of forests worldwide.

2. Forest Economics and Management

Forest management is a dynamic problem because trees take time to grow. The seminal model of the optimal rotation time for a forest was developed by Faustmann (1849) and elaborated upon by Samuelson (1976). Since then, the Faustmann model has been extended in many ways (Newman, 1988), including to even-aged forest management (Jackson, 1980; Chang, 1983), uneven-aged forest management (Chang, 1981; Hall, 1983), externalities (Berck, 1981; Bowes, 1983; Calish et al., 1978; Hartman, 1976; Nguyen, 1979; Strang, 1983), taxation (Chang, 1982; Klemperer, 1979; Pearse, 1967; Rideout, 1982; Ollikainen, 1991), evolving stumpage price (Bare and Waggener, 1980; Gregersen, 1975; McConnell et al., 1983; Hardie et al., 1984; Newman et al., 1985), a one-time change of unchanged factors (Nautiyal and Williams, 1990), uncertainty (Chang, 1998), the intertemporal allocation of consumption (Deegen et al., 2011), rotation and thinning (Arimizu, 1958), optimal density (Amidon and Akin, 1968), net present discounted value of future payoff (Kilkki and Väisänen, 1969), forest production control (Hool, 1965), production control with Markov process (Hool, 1966), and thinning decisions (Amidon and Akin, 1968). The previous literature has also examined more complicated thinning decisions or combined thinning and rotation decisions (Amidon and Akin, 1968; Brodie et al., 1978; Brodie and Kao, 1979; Chen et al, 1980; Ritters et al., 1982).

In most of the forest economics literature, growth simulation models or yield models characterize the objective as the timber yield for tree species of interest in dynamic programming. Growth simulation models and yield models both describe the productivity of a tree standing as a function of multiple variables such as age, temperature, soil, rainfall, slope, and rooting depth (Tyler, Macmillan, and Dutch, 1996). If the objective of the forest owners is instead profit maximization (Buongiorno, and Gilless, 2003; Kant and Alavalapati, 2014), then the market price of the timber also becomes a significant factor in the payoff function.

Sophisticated studies on forestry management utilizing dynamic optimization typically focus on developed countries (Ritters, 1982; Haight, 1985; Yousefpour and Hanewinkel, 2009). Pine and fir are two major types of tree species that researchers are interested in, due to their popularity in the western world and well developed productivity simulation models, and since these tree species are expensive to manage, requiring intensive thinning machinery and labor. Dynamic models have also been developed to study other topics relevant to forest resources, including apple tree pollination (Wilcox et al., 2024), organic farming (Meneses et al., 2024), agricultural groundwater management (Sears et al., 2019, 2024a, 2024b, 2024c), and agricultural disease control (Carroll et al., 2019, 2024a, 2024b; Sambucci et al., 2024; Yeh et al.,2024). Fewer studies have been carried out in developing countries and poor areas, where the need for sustainable forest management is particularly acute, and where different political structures, forestry contexts, objectives, and previous sivilcultural practices demonstrate various research opportunities for forest management.

In Wu et al. (2024), we innovate on the previous literature by developing a novel nested dynamic bioeconomic model of the management of forests that generate interdependent products that differ in their growth cycles; and by analyzing bamboo forest management in particular. We apply our model to detailed daily panel data on bamboo shoot and bamboo stem harvests, in order to assess the optimality of bamboo farmers' forest management strategies and to understand the beliefs and perceptions that underlie and rationalize their management strategies. Both bamboo shoots and bamboo stems are valuable products. The harvesting of bamboo stems entails cutting down the bamboo plant, while the harvesting of bamboo shoots -- which grow annually from the bamboo plant -- does not. To solve for the optimal bamboo forest management strategy, our novel nested dynamic bioeconomic model nests an inner finite-horizon within-year daily dynamic programming problem that captures daily bamboo shoot growth within a season, inside an outer finite-horizon between-year annual dynamic programming problem that captures annual bamboo stem growth from year to year. Our nested dynamic bioeconomic model has important implications for the sustainable management of forests worldwide, particularly when the forests produce products that can be harvested at more frequent intervals than the trees themselves.

3. Modeling Framework

We present a framework for stochastic dynamic bioeconomic modeling of optimal forest management under uncertainty consisting of several key components.

A first key component of a bioeconomic model of forest management are biological production functions for the forest resources being managed, which may include the trees or plants themselves, as well as any products (such as fruits, nuts, etc.) that grow on the trees or plants. The choice of the functional form and/or parameter values for the biological production functions is best informed by relevant scientific information from biology, plant sciences, and forest science, and should be as specific as possible to the respective forest resource and species being managed. In our research on bamboo forest management in Wu et al. (2024), for example, we model each of the products from a bamboo forest using a separate Chapman-Richards model (Richards, 1959), which is a flexible growth model for plants suggested by biological studies (Liu and Li, 2003) that has been used for bamboo (Yen, 2016), and we calibrate the parameters using data and information from previous studies of bamboo growth in the scientific, biological, and plant science literature.

A second key component are the choice variables a faced by the forest manager. Typically the choice variables likely include the harvesting decisions for the various forest resources being managed. In our research on bamboo forest management in Wu et al. (2024), for example, our action variables are the harvest decisions for each of the bamboo forest products we model.

A third key component is to characterize the sources of uncertainty. In our research on bamboo forest management in Wu et al. (2024), for example, we allow precipitation, prices, and the possibility of bamboo shoots death to all be stochastic. For both precipitation and prices, we use the empirical distribution of precipitation and prices in the data. For the possibility of bamboo shoots death, we calibrate the probability of death using data and information from previous studies of bamboo growth in the scientific, biological, and plant science literature.

A fourth key component are the state variables s. These state variables should include state variables affected by the choice variables, such as vairables measuring the state and/or quantity of the forest resources being managed, and may also include variables related to the sources of uncertainty. In our research on bamboo forest management in Wu et al. (2024), our state variables included the number of each of the bamboo products we modeled, precipitation, and prices.

A fifth key component is to specify the per-period payoff (or per-period net benefits) $\pi(a, s)$ to the forest manager as a function of the action and state variables. In the case of forest businesses, the per-period payoff is typically the per-period profit. In our research on bamboo forest management in Wu et al. (2024), the per-period payoff was daily profit, as calculated by the total revenue of all the forest products being harvested that day, minus the total cost of harvesting all the forest products being harvested that day.

Combining the above five key components, one can construct the value function, which is the present discounted value (PDV) of the entire stream of per-period payoffs when the forest resource harvest decisions are chosen optimally, via the following Bellman equation (Bellman, 1954):

$$v(s) = \max_{a} \pi(a, s) + \beta E[v(s')|s, a]. \tag{1}$$

If the solution to the dynamic programming problem (1) yields an optimal strategy that differs from forest managers' actual decisions, then, to the extent that some of the differences between actual behavior and optimal strategy reflect possible sub-optimal behavior on the part of forest managers, the model may suggest ways to improve forest management and policy. Our research and framework have important implications for the sustainable management of forests worldwide.

References

Amidon, E.L., and G.S. Akin. (1968). Dynamic programming to determine optimum levels of growing stock. Forest Science, 14(3), 287-291.

Arimizu, T. (1958). Regulation of the cut by dynamic programming. Journal of the Operations Research Society of Japan, 1(4), 175-182.

Bare, B.B., and T.R. Waggener. (1980). Forest land values and return on investment. Forest Science, 26(1), 91-96.

Bellman, R. (1954). The theory of dynamic programming. Bulletin of the American Mathematical Society, 60(6), 503-515.

Berck, P. (1981). Optimal management of renewable resources with growing demand and stock externalities. Journal of Environmental Economics and Management, 8(2), 105-117.

Bowes, M.D. (1983). Economic foundations of public forestland management. Resources for the Future.

Brodie, J.D., and C. Kao. (1979). Optimizing thinning in Douglas-fir with three-descriptor dynamic programming to account for accelerated diameter growth. Forest Science, 25(4), 665-672.

Brodie, J.D., D.M. Adams, and C. Kao. (1978). Analysis of economic impacts on thinning and rotation for Douglas-fir, using dynamic programming. Forest Science, 24(4), 513-522.

Buongiorno, J., and J.K. Gilless. (2003). Decision Methods for Forest Resource Management. Academic Press, San Diego.

Bystriakova, N., V. Kapos, I. Lysenko, and C.M.A Stapleton. (2003). Distribution and conservation status of forest bamboo biodiversity in the Asia-Pacific Region. Biodiversity & Conservation, 12(9), 1833-1841.

Calish, S., R.D. Fight, and D.E. Teeguarden. (1978). How do nontimber values affect Douglas-fir rotations?. Journal of Forestry, 76(4), 217-221.

Carroll, C.L., C.A. Carter, R.E. Goodhue, and C.-Y.C. Lin Lawell. (2019). Crop disease and agricultural productivity: Evidence from a dynamic structural model of verticillium wilt management. In W. Schlenker, editor, Agricultural Productivity and Producer Behavior, pages 217–249. University of Chicago Press, Chicago.

Carroll, C.L., C.A. Carter, R.E. Goodhue, and C.-Y.C. Lin Lawell. (2024a). The economics of decision-making for crop disease control. Working paper, Cornell University. URL: http://clinlawell.dyson.cornell.edu/Vwilt_short_long_paper.pdf

Carroll, C. L., C.A. Carter, R.E. Goodhue, and C.-Y.C. Lin Lawell. (2024b). Supply chain externalities and agricultural disease. Working paper, Cornell University. URL: http://clinlawell.dyson.cornell.edu/spinach_seed_paper.pdf

Chang, S. (1982). An economic analysis of forest taxation's impact on optimal rotation age. Land Economics, 58(3), 310-323.

Chang, S.J. (1981). Determination of the optimal growing stock and cutting cycle for an uneven-aged stand. Forest Science, 27(4), 739-744.

Chang, S.J. (1983). Rotation age, management intensity, and the economic factors of timber production: Do changes in stumpage price, interest rate, regeneration cost, and forest taxation matter? Forest Science, 29(2), 267-277.

Chen, C.M., D.W. Rose, and R.A. Leary. (1980). Derivation of optimal stand density over time—a discrete stage, continuous state dynamic programming solution. Forest Science, 26(2), 217-227.

Deegen, P., M. Hostettler, and G.A. Navarro. (2011). The Faustmann model as a model for a forestry of prices. European Journal of Forest Research, 130(3), 353-368.

Dong, D., Y. Tong, X. Yi., C. Zhang, and M. Gu. (2015). Harvesting cost and economics efficiency analysis of bamboo forests in various slope hill lands. Journal of Bamboo Research, 34(4), 23-27. [in Chinese]

Faustmann, M. (1849). Calculation of the value which forest land and immature stands possess for forestry. General Journal of Forestry and Hunting. [in German]

Food and Agriculture Organization [FAO]. (2005). Global Forest Resources Assessment 2005.

Food and Agriculture Organization [FAO]. (2015). Global Forest Resources Assessment 2015.

Gregersen, H.M. (1975). Effect of inflation on evaluation of forestry investments. Journal of Forestry, 73(9), 570-572.

Haight, R.G. (1985). A comparison of dynamic and static economic models of uneven-aged stand management. Forest Science 31(4), 957-974.

Hall, D.O. (1983). Financial maturity for even-aged and all-aged stands. Forest Science, 29(4), 833-836.

Hardie, I.W., J.N. Daberkow, and K.E. McConnell. (1984). A timber harvesting model with variable rotation lengths. Forest Science, 30(2), 511-523.

Hartman, R. (1976). The harvesting decision when a standing forest has value. Economic Inquiry, 14(1), 52-58.

Jackson, D. H. (1980). The Microeconomics of the Timber Industry. Westview Press.

Kant, S., and J.R.R. Alavalapati. (2014). Handbook of Forest Resource Economics. Abingdon: Routledge.

Kilkki, P., and U. Väisänen. (1969). Determination of the optimum cutting policy for the forest stand by means of dynamic programming. Acta Forestalia Fennica, 102.

Klemperer, W.D. (1979). Inflation and present value of timber income after taxes. Journal of Forestry, 77(2), 94-96.

Kling, C.L., R.W. Arritt, G. Calhoun, and D.A. Keiser. (2017). Integrated assessment models of the food, energy, and water nexus: a review and an outline of research needs. Annual Review of Resource Economics, 9(1), 143-163.

Kusters, K., and B. Belcher. (2004). Forest Products, Livelihoods and Conservation: Case studies of non-timber forest product systems. Volume 1 - Asia. Center for International Forestry Research (CIFOR).

Liu, Z.-G., and F.-R. Li. (2003). The generalized Chapman-Richards function and applications to tree and stand growth. Journal of Forestry Research, 14(1), 19-26.

Matthews, R. (2012). The economic and employment benefits of forests. Eco-Business, 7 March 2012.

McConnell, K.E., J.N. Daberkow, and I.W. Hardie. (1983). Planning timber production with evolving prices and costs. Land Economics, 59(3), 292-299.

Meneses, M.A., C.L. Casteel, M.I. Gómez, D.R. Just, R. Kanbur, D.R. Lee, and C.-Y.C. Lin Lawell. (2024). Organic farming transitions: A dynamic bioeconomic model. Working paper, Cornell University. URL: https://clinlawell.dyson.cornell.edu/organic_transitions_paper.pdf

Nautiyal, J.C., and J.S. Williams. (1990). Response of optimal stand rotation and management intensity to one-time changes in stumpage price, management cost, and discount rate. Forest Science, 36(2), 212-223.

Newman, D.H., C.B. Gilbert, and W.F. Hyde. (1985). The optimal forest rotation with evolving prices. Land Economics, 61(4), 347-353.

Newman, D.H. (1988). The optimal forest rotation: A discussion and annotated bibliography. Gen. Tech. Rep. SE-48. Asheville, NC: US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Nguyen, D. (1979). Environmental services and the optimum rotation problem in forest management Journal of Environmental Management, 8(2), 127-136

Ollikainen, M. (1991). The effect of nontimber taxes on the harvest timing—the case of private nonindustrial forest owners: A note. Forest Science, 37(1), 356-363.

Pearse, P.H. (1967). The optimum forest rotation. The Forestry Chronicle, 43(2), 178-195.

Richards, F. (1959). A flexible growth function for empirical use. Journal of Experimental Botany, 10(2), 290-301.

Rideout, D.B. (1982). Micro-Economic Properties of Four Local Forest Tax Methods. (doctoral dissertation). University of Washington, Seattle, United States.

Riitters, K.H.; J.D. Brodie, and D.W. Hann. (1982). Dynamic programming for optimization of timber production and grazing in ponderosa pine. Forest Science, 28(3), 517-526.

Sambucci, O., C.-Y.C. Lin Lawell, and T.J. Lybbert (2024). Pesticide spraying and disease forecasts: A dynamic structural econometric model of grape growers in California. Working paper, Cornell University. URL: https://clinlawell.dyson.cornell.edu/PMI_dynamic_paper.pdf

Samuelson, P.A. (1976). Economics of forestry in an evolving society. Economic Inquiry, 14(4), 466-492.

Sears, L., D. Lim, and C.-Y.C. Lin Lawell. (2019). Spatial groundwater management: A dynamic game framework and application to California. Water Economics and Policy, 5(1):1850019.

Sears, L., C.-Y.C. Lin Lawell, G. Torres, and M.T. Walter. (2024a). Adjudicated groundwater property rights: A structural model of the dynamic game among groundwater users in California. Working paper, Cornell University. URL: https://clinlawell.dyson.cornell.edu/property_rights_struc_paper.pdf

Sears, L., C.-Y.C. Lin Lawell, G. Torres, and M.T. Walter. (2024b). Moment-based Markov equilibrium estimation of high-dimension dynamic games: An application to groundwater management in California. Working paper, Cornell University. URL: https://clinlawell.dyson.cornell.edu/mme_groundwater_paper.pdf

Sears, L., C.-Y.C. Lin Lawell, and M.T. Walter. (2024c). Groundwater under open access: A structural model of the dynamic common pool extraction game. Working paper, Cornell University. URL: https://clinlawell.dyson.cornell.edu/open_access_structural_paper.pdf

Strang, W.J. (1983). On the optimal forest harvesting decision. Economic Inquiry, 21(4), 576-583.

Tyler, A.L., D.C. MacMillan, and J. Dutch. (1996). Models to predict the General Yield Class of Douglas fir, Japanese larch and Scots pine on better quality land in Scotland. Forestry: An International Journal of Forest Research, 69(1), 13-24.

Wilcox, S.W., D.R. Just, C.-Y.C. Lin Lawell, M.I. Gómez, and H. Grab. (2024). To (rent) bees or not to (rent) bees?: An examination of the farmer's question. Working paper, Cornell University. URL: https://clinlawell.dyson.cornell.edu/rent_bees_paper.pdf

Wu, T., D.R. Just, C.-Y.C. Lin Lawell, J. Zhao, Z. Fei, A. Ortiz-Bobea, and Q. Wei. (2024). Optimal forest management for interdependent products: A nested dynamic bioeconomic model and application to bamboo. Working paper, Cornell University. URL: https://clinlawell.dyson.cornell.edu/Moso_bamboo_dynamic_paper.pdf

Yeh, D.A., M.I. Gómez, and C.-Y.C. Lin Lawell. (2024). Sustainable pest management, beliefs, and behavior: A dynamic bioeconomic analysis. Working paper, Cornell University. URL: https://clinlawell.dyson.cornell.edu/Maine_SWD_dynamic_bioeconomic_paper.pdf

Yen, T.-M. (2016). Culm height development, biomass accumulation and carbon storage in an initial growth stage for a fast-growing Moso bamboo (Phyllostachy pubescens). Botanical Studies, 57(1), 10.

Yousefpour, R., and M. Hanewinkel. (2009). Modelling of forest conversion planning with an adaptive simulation-optimization approach and simultaneous consideration of the values of timber, carbon and biodiversity. Ecological Economics, 68(6), 1711-1722.