ABSTRACT


Two areas of study important to forest economics are aggregate macroeconomic behavior and behavior of individual forest landowners. However, the connection between individuals and the aggregate is not well-studied. Agent-based modeling shows promise as a means of aggregating individual decisions in a theoretically consistent manner. Furthermore, this approach is capable of capturing heterogeneity in landowners that macroeconomic approaches ignore. The Forest Agent-Based Landowner Economy (FABLE) model aggregates landowner behavior by simulating a market where agents use different decision-making calculations (fixed rotation Faustmann, reservation price Faustmann and reservation price Hartman) to cast bids. The model outputs include price, removals, inventory, average harvest age and supply elasticity. The results demonstrate that the share of market participants using a given decision rule has an impact on the aggregate market dynamics. FABLE also produces a novel price bubble effect endogenously when the simulated market is out of equilibrium.
Aggregate Implications of Theoretical Forest Landowner Behavior: An Agent-Based Modeling Approach

by
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DEDICATION

To mine.
BIOGRAPHY

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INTRODUCTION

The forest economics literature addresses two topics thoroughly: individual forest landowner behavior and aggregate market behavior. But less common are efforts to connect these two major areas of study. Understanding the implications of individual decisions to aggregate market behavior is the topic of this research.

Forest Economics and Decision Making

At the level of individual forest landowners, the literature proposes many ways to harvest optimally. The classical method of optimizing a harvest is that of Faustmann, where landowners choose a timber rotation period based on the discounted value of timber. For this calculation, the discount rate is an assumption, and models within the literature often use an aggregate, average discount rate (Newman, Gilbert, & Hyde, 1985; Thomson, 1992). In reality, the appropriate discount rate for a particular landowner is their own real discount rate, and discount rates vary among individuals (Atmadja, 2008). Furthermore, the traditional Faustmann approach does not account for uncertainty of future prices.

Amendments to the Faustmann formula which take into account uncertainty and risk are present in the literature (Norstrom, 1975; Hartman, 1976; Routledge, 1980; Koskela, 1989; Pukkala & Kanga, 1996; Zhang, 2001). Such corrections tend to involve stochastic programming under an assumption that prices are either stationary (that prices fluctuate around some average) or non-stationary (that future prices may deviate significantly from the current price) (McGough, Plantinga, & Provencher, 2004). The general conclusion of a Faustmann formula that takes into account uncertainty is that optimal harvesting takes place
with a reservation price rule, wherein a landowner delays harvest until the next period as long as the market price is below the price a landowner expects (McGough, Plantinga, & Provencher, 2004).

No consensus exists on the effect that real price increases have on optimal timber rotation. For example, whereas Jackson posited that continuous real price increases cause a shortening of rotations over time, Hyde proposed “the effect to be uncertain due to the conflicting effects of price level and the rate of price increase” (Newman, Gilbert, & Hyde, 1985).

In addition to landowners placing value on timber harvests, some landowners also place value on standing forests. When the value of a standing forest increases with stand age, the optimal rotation is lengthened (Hartman, 1976). Furthermore, if the value of a standing forest is high enough, it may be optimal to never harvest (Hartman, 1976). Hartman suggested that increasing value with stand age is a reasonable formulation for recreational and other values (Hartman, 1976).

Another important perspective in the literature is that landowners may seek to maximize utility instead of profit. In this regard, landowner demographics and preferences are important factors in harvest behavior in addition to economic considerations and land attributes (Amacher, Conway, & Sullivan, 2003). The conclusion of this branch of research is that while “price is a major determinant of the propensity to harvest timber,” other characteristics (tract size, ownership objectives, affluence, etc.) affect the likelihood that a landowner will harvest (Binkley, 1981).
Heterogeneity of Forest Landowners

The diversity of considerations that may contribute to harvesting decisions is reflected in the identified goals of forest landowners. The forest landowner literature reveals that “forest landowners … are motivated by a set of values which requires a management plan specifically geared toward their desired end” (Finley & Kittredge, 2006). When surveys ask forest landowners about their reason for ownership, responses are diverse. For example, from a cluster analysis of National Woodland Owner Survey data, researchers found that a portion of landowners primarily own forest for profit from harvests, while other landowners value profit and environmental services or environmental services alone (Majumdar, Teeter, & Butler, 2008). The same survey showed that "environmental values, recreation, investment/income, non-instrumental values, home/quality of life, and incidental ownership" are among motivations for owning forested land (Bengston, Butler, & Asah, 2009). A Massachusetts study of landowners identified three primary clusters: (1) “Thoreau,” who value privacy, scenic beauty, recreation and timber, (2) “Muir,” who value preservation of nature and environmental quality, and (3) “Jane Doe,” a minority who are prone to development (Finley & Kittredge, 2006). Yet another study classified landowner motivations within the categories of “Multiobjective, Recreationists, Self-employed owners, Investors, and Indifferent owners” (Favada, Karppinen, Kuuluvainen, Mikkola, & Stavness, 2009). The classifications in these landowner surveys are consistent with a combination of heterogeneous Faustmann and Hartman agents.

The literature presents three major ways of aggregating the behavior of landowners—by constructing “engineering” models, by making a direct econometric analysis (Wear &
Parks, 1994), or by expanding probit models of representative stands to a regional level (Prestemon & Wear, Linking Harvest Choices to Timber Supply, 2000). Supply functions for an engineering approach are estimated by “applying estimated decision rules to a variable forest inventory” (Wear & Parks, 1994). In effect, this method treats the aggregate decision rule as the sum of the parts (individual decision rules). Econometric models are statistical in nature, are calibrated by empirical evidence, and derive their structure from rational behavioral assumptions (Wear & Parks, 1994). However, this technique is hard-pressed to provide detail on forest structure, and econometric models lose accuracy beyond the short run (Wear & Parks, 1994). Despite substantial research in these areas, Wear and Parks suggest that:

“…the greatest opportunity for future advances is at the interface between individual harvest rules and their aggregate supply consequences. Aggregate models built through a theoretically consistent aggregation of individual choice models hold great promise for improving knowledge and forecasts of timber supply.”

(Wear & Parks, 1994)

The probit model approach advanced by Prestemon and Wear is a step toward linking individual harvest choices to aggregate supply (Prestemon & Wear, 2000). This technique does differentiate between different types of landowners. Aggregation for each ownership type in this approach is calculated as the sum of parts (multiplying by an expansion factor) (Prestemon & Wear, 2000). However, a model of this type is agnostic toward landowner decisions or motivations and is based on data generated by the market as a whole.
The early attempts to directly link optimized microeconomic decisions to macroeconomic behavior relied on a representative agent assumption (Nerlove & Bessler, 2001). However, the representative agent assumption is not valid when heterogeneity is present (Nerlove & Bessler, 2001). A modern realization is that “aggregate implications of micro theory can only be found by explicit modeling of heterogeneity” (Forni & Lippi, 1999). The question that arises is what heterogeneous aspects of agents are important to the aggregate picture. Also important is finding a method to explicitly model heterogeneity.

Agent-Based Modeling

Agent-based modeling may help show the aggregate impact of different harvest decision-making rules while aggregating through a simulated market. Agent-based modeling (also called multi-agent systems or multi-agent simulation) is a computational method which has seen a substantial increase in the number of applications since the early 1990s due to improvements in computer processing speed (Gilbert, 2006). An agent-based model (ABM) has a few characteristic features. The agents (for example, economic actors, in the case of a market) may: be heterogeneous, interact with an environment and/or each other, possess bounded rationality (limits on information or biases in perception), and be capable of learning. The interactions among agents with differing behavioral heuristics give rise to a larger macroscopic pattern. Because the macroscopic behavior is not defined directly, evolutionary or complex adaptive changes may result from an ABM. The method is thus suited to social science applications.
Agent-based modeling has been applied toward problems in various fields. A prominent branch of study that uses agent-based modeling is agent-based computational economics (ACE) (Tesfatsion, 2001). Also called “artificial markets,” work in ACE has ranged from modeling wholesale fish markets to asset pricing and evolving decision making to information economics (Schredelseker & Hauser, 2008). In environmental science, researchers have attempted to understand dynamics of ecosystem services, where individual landowner actions impact connectivity within a landscape (Satake, Leslie, Iwas, & Levin, 2007). In addition, agent-based modeling has been used in forestry to determine optimum harvesting decisions when pine beetle infestations create uncertainty (Schwab, Maness, Bull, & Roberts, 2009).

Among aggregation techniques discussed above, an agent-based model differs most sharply with econometric methods. Whereas econometric methods model macroeconomic variables in terms of how those macroeconomic variables behaved in the past, agent-based models use a bottom up approach that can lead to novel or nonlinear behaviors. The following diagram illustrates this distinction (Figure 1).
Figure 1. (a) An econometric model uses past macroeconomic (aggregate) data to simulate the future. (b) An agent-based model uses a bottom-up approach to simulate emergent phenomena, using simulated markets to aggregate to the whole.

A common way of simulating a market with agent-based modeling is through bidding (Tesfatsion, 2002). Examples of bidding regimes are English auctions, where the price is raised until the last bidder remains, sealed bid auctions, where agents cast bids secretly, or other more complex auctions (Tsvetovatyy, Gini, Mobasher, & Wieckowski, 1997). However, the most appropriate and easily executed bidding mechanism for ABM is a private-value auction, "where an agent’s reservation price can be totally determined locally and is independent from other agents’ reservation prices" (Tsvetovatyy, Gini, Mobasher, & Wieckowski, 1997). An auction formulated in this way eliminates the need to model strategic behavior and iterative bidding (Tsvetovatyy, Gini, Mobasher, & Wieckowski, 1997).
Objectives

No previously developed agent-based model addresses the aggregate implications of theoretical forest landowner behavior. In addition, previous methods for aggregating individual behavior have not taken advantage of market simulation (through bidding by individuals) as a method of aggregation in itself. Studying the interactions through a market of forest landowner agents could shed new light on what happens to forests and markets when various theoretically “optimal” harvesting heuristics are applied. With this goal in mind, the objectives of this study are to:

1. Develop an agent-based timber market model which simulates inventory, removals and prices which emerge from three decision making functions in five cases:
   a. A case of only “fixed rotation Faustmann” landowners, who decide to harvest at a fixed rotation age based on a Faustmann rotation calculation, irrespective of the market price.
   b. A case of only “reservation price Hartman” landowners, who decide to harvest by placing value on a standing forest in addition to a Faustmann calculation, but delay harvest if the market price is below the price they desire.
   c. A case of only “reservation price Faustmann” landowners, who use a Faustmann formula to optimize harvest, but delay harvest if the market price is below the price they desire.
d. A case of 66% reservation price Faustmann and 34% reservation price Hartman landowners.

e. A case of 34% reservation price Faustmann and 66% reservation price Hartman landowners.

2. Determine the market features that result from each case.

3. Determine the supply response to different demand levels and the implications for sustainability.

METHODS

This analysis focuses on a generic pine forest in the southern United States. This forest type and region are the highest valued and most managed, and is thus a relevant subject for forest economic analysis. Furthermore, hardwoods are not usually planted in even-aged stands, so using even-aged pine stands is both more realistic and convenient.

Developing a computer model for this problem is useful because the problem involves dynamic interactions among variables. In particular, the biophysical and market elements of the problem cannot be fully assessed or described with a static analysis, and computer models have a history of use in simulating dynamic problems in social and physical sciences.

Economic modeling of forest resources can take a few approaches. Various econometric models are used to examine trends on macroeconomic variables (Beach, Pattanayakp, Yanga, Murray, & Abt, 2005). However, none of these approaches are suited to generating markets from the behavior of heterogeneous individuals because: 1) they are
methods that deal with aggregate variables, or 2) scaling down to an individual assumes that all individuals are average. In contrast, agent-based modeling is uniquely suited to modeling individual behavior and allowing the aggregate picture to arise endogenously. In order to understand the aggregate implications of theoretical forest landowner behavior, each individual agent should be able to apply a rule specific to their situation. Agent-based modeling allows for this because agents can perceive their environment, perform actions, store information about the past, and follow a set of heuristics (Gilbert, 2006).

Agent-based models can be built from any object-oriented programming language or from one of several pre-built software packages. Software packages are preferable because they have been debugged and evaluated by thousands of users. Popular packages include Repast, Swarm and Netlogo. Among these NetLogo was chosen for three reasons: (1) it is free, (2) it employs a simple library of java-based commands that are easily understood by novice to intermediate programmers, and (3) NetLogo has an active online community of fellow users who voluntarily help new users with troubleshooting. Furthermore, NetLogo has been used to create thousands of agent-based models since 1999.
An Agent-Based Mental Model

Outlining a mental conception of key actions in an appropriate order provides a foundation for model construction. The following mental model is useful for the present study:

1. Agents are heterogeneous in three ways:
   a. Agent type: Fixed rotation Faustmann agents harvest after a fixed rotation period. Reservation price Faustmann agents harvest if the market price meets or exceeds their expected price. Reservation price Hartman agents perform identically to reservation price Faustmann agents, but place value on a standing forest as its age increases.
   b. Agents are randomly assigned a real discount rate between 3% and 7%, inclusive. A survey of limited resource woodland landowners found discount rates to range between 2% and 9% (Atmadja, 2008).
   c. Agents start with a random draw from a tree age class distribution associated with their agent type.

2. Each agent performs a calculation that seeks to maximize their wellbeing.

3. Agents participate in a market by casting bids in a private value auction with a single iteration. Each agent assumes last year’s price will be the price in the future.

4. Assuming a deterministic tree growth function, each agent discounts the future value (at multiple time steps) of their stand to obtain a list of present values. They divide the maximum present value derived from these calculations by present quantity to obtain a present price at which they would be willing to sell.
5. Agents report their individual prices (bids) in order from least to greatest, creating a ranked list for bidding.

6. The agent with the lowest price harvests, followed by the second lowest, and so on until demand is met (a demand curve is exogenously defined by a “demand level” parameter and adjusts to price changes according to an assumed demand elasticity).

7. The highest bid that is required to meet demand becomes the market price of the current year. All agents get this price; any amount above their bid is akin to a producer surplus.

8. Demand elasticity, the change in price between last year and the current year, and quantity demanded this year are used to determine demand for next year.

9. The year is advanced by one and steps 3 through 9 are repeated until the desired model run period is reached.

Software and Coding Considerations

Researchers commonly adopt descriptive and efficient acronyms for models. The present model is called Forest Agent-Based Landowner Economy (FABLE). This acronym identifies the forestry context, the unique agent-based approach, and the landowner-derived economy that arises from the model. Wikipedia defines a fable as a “succinct story … that features … inanimate objects, or forces of nature, which are anthropomorphized.” FABLE is true to this definition in the sense that agents in the model are given “human” qualities. Furthermore, in terms of a story, FABLE seeks to provide a useful narrative that connects agent actions with the big picture.
Choosing an agent type appropriate to the problem is an important initial step in developing an agent-based model. The types of agents in NetLogo are turtles, patches, links and the observer. Turtles move around the environment and can be programmed to interact with other turtles and patches. Patches are rectangular stationary regions which have coordinates and typically represent an environment. Links connect two turtles, and the observer (in practice, the user) provides commands to all other agents. For this analysis, turtles, and thus links, were irrelevant because simulating actions on a stationary timber stand is conducive to using the patch agent type.

NetLogo contains a library of working reference models which provide first-time programmers with efficient coding solutions. FABLE adopts segments of code for displaying plots from the AIDS model by Uri Wilensky. In addition, code was adopted from the Continental Divide model by Uri Wilensky and modified for the purposes of the model.

Tree Growth and Decision-making

Data from the Hofmann forest provided a functional form for timber growth. However, because the polynomial function (of order 4) was unrealistic at high and low ages, the function was computationally truncated at ages prior to 7 and after 51. So the stock of trees (amount of biomass) on quarter-acre stands that are between 7 and 51 years of age is given by:

$$f(x) = \frac{(84.546 + 0.007x^4 - 0.7415x^3 + 23.941x^2 - 107.33x)}{4}$$
If a stand is less than 7 years old, FABLE sets the stock equal to 1, and the plot cannot be harvested. If a stand is greater than 51 years old, FABLE sets the stock equal to the stock at 51 years old.

Given a deterministic growth function the value of a stand at a future time (FV) is the product of price and the stock. But harvesting always occurs in the present, so present value of that stand (PV) requires discounting at an assumed interest rate according to the following function:

\[ PV = FV/(1 + r)^t \]

Where \( r \) is the real discount rate and \( t \) is time. The object of a fixed rotation Faustmann calculation is to find the value of \( t \) that maximizes present value. In FABLE, each agent using a fixed rotation Faustmann rule makes a calculation based on their own interest rate. Because fixed rotation Faustmann agents are harvesting at a certain rotation length (time), irrespective of price, they cast a bid equal to last year’s price minus a random dollar amount between 0 and 5. Thus, fixed rotation Faustmann agents will always be the first to sell their timber.

Reservation price Faustmann agents perform the above calculation in each time step to obtain a present value. They then divide that value by the current stock of their stand to obtain a price, or bid. The bids from all agents are ordered from least to greatest. Agents with the lowest bids harvest first, and the amount of biomass from the stand is added to the supply. The process repeats until quantity supplied equals quantity demanded, and the final bid required to achieve this equivalence becomes the price in the current time period.

Reservation price Hartman agents follow the same bidding procedure as reservation price
Faustmann agents with a reservation price, except reservation price Hartman agents add value for a standing forest in proportion to the square of a stand’s age:

\[ PV = (FV + Ht^2)/(1 + r)^t \]

where \( H \) is a Hartman parameter that controls the scale of amenity values. \( H \) is set equal to \$0.75 for the purposes of this research, but this assumption is tested in the sensitivity analysis.

**Assumptions**

FABLE contains several parameters that are set as initial conditions for the model. When the model is initialized, the parameters do not change. Because the parameters are assumptions, defensible settings are chosen for each model run. In cases where no educated guess or literature source can provide guidance on the parameter, the model is run at multiple values of the parameter in order to determine the impact an assumption has on model results.

Parameters controlling the mix of landowner decision rules are one class of assumptions. In FABLE, the total number of forested acres is 1056.25. Each quarter of an acre represents a stand with a single age class of trees. Each stand can be harvested according to either fixed rotation Faustmann, reservation price Faustmann, or reservation price Hartman decision rules, and each stand has a separate bid. Each year, agents cast approximately 4000 bids, and only a small fraction are successful; thus, agents are pricetakers. The “faustmanfix” parameter controls the percentage of stands that employ a fixed rotation Faustmann rule. Similarly, the “faustmannres” parameter controls the percentage of stands employing a reservation price rule based on Faustmann. Any remaining percentage of stands not claimed...
by the faustmannfix and faustmannres parameters is automatically assigned to the reservation price Hartman decision rule.

In FABLE demand responds to market prices assuming a fixed demand curve with a demand elasticity of -0.5. The fixed demand curve is determined by the price0 parameter and the demand level parameter, where price0 is an initial price and demand level is a corresponding initial demand level in 10 thousands of green tons. For simulations, price0 is set to an initial value of $30 for all model runs. Model runs take place for the demand level parameter for values between 8 and 20 with an increment of 2 (that is, between 80,000 green tons and 200,000 green tons with an increment of 20,000 green tons). Adjusting the demand level upward is equivalent to shifting the demand curve to the right on a price vs. quantity plot (Figure 2).

Figure 2. Initial conditions for price and quantity demanded by demand level.
Due to the bidding process, it is possible that low-bidding agents become depleted, leaving the highest bidders to drive price up unrealistically. In the real world, constraints exist on price increases at the regional level because, for example, producers outside the region might offer lower prices. Extending the logic, if consumers within the region wish to purchase wood from outside the region, they would have to pay for transporting the wood. FABLE implements such a constraint on the price increase per year; the current year’s price may not rise above last year’s price by more than the “transportation cost parameter.” This parameter may also be interpreted to represent other factors that increase the cost of importing. In FABLE, this parameter is fixed at $10 per green ton for each model run.

*Realism of the Acreage and Ownership Assumptions*

At this point, it is important to note that the scale of the acreage (1056.25 acres) and demand level values (80,000 to 200,000 green tons per year) does not impact the realism of the model. If 10 million acres are preferable, one would simply multiply the growth function by the appropriate scalar and simultaneously increase the demand level by the same amount (since the range of demand levels is important toward the end of producing interesting phenomena). Doing so would increase the minimum autonomous tract size. If the acreage were scaled up to 10 million for example, the minimum autonomous tract size would be 2367 acres. Tracts of this size can be mentally lumped together to simulate the fact that some landowners own more land than others (even orders of magnitude). The only barrier to this “mental lumping” process is the percentage of tracts managed according to a given decision rule, but this factor is controlled by the faustmanres and faustmanfix parameters. To illustrate
this point, consider the majority reservation price Faustmann case, where the faustmanres parameter is set to 66. In this case, 66 percent of the land is managed according to the reservation price Faustmann decision and 34 percent is managed according to the reservation price Hartman decision. A histogram shows the initial age class distribution of tracts, separated by decision type (Figure 3). Conceptually, one can consider that a landowner who owns a large amount of land owns several tracts within either the reservation price Faustmann or reservation price Hartman portion.

![Histogram of initial age class distribution of tracts by decision type for the majority reservation price Faustmann case.](image-url)
**Response Metrics**

In addition to validating the model construction by consulting the literature, post-validation is necessary to confirm that the model produces reasonable results. A measure of supply elasticity serves this function in FABLE. Empirical evidence shows that forest landowners generally exhibit an inelastic harvest response to price increases, but measured supply elasticities range from 0.2 to 9.8 depending on landowner characteristics and methodology (Pattanayak, Murray, & Abt, 2002). In a more specific study, the price elasticity of non-industrial private forest landowners with a short rotation has been measured as between 0.22 and 0.33 (Newman & Wear, 1993). In FABLE, supply elasticity is related to the change in quantity supplied and the change in price according to the following formula:

\[
E_s = \frac{Q_{j+1} - Q_j}{Q_j} \cdot \frac{P_{j+1}}{P_{j+2} - P_{j+1}}
\]

Because FABLE is a supply side model and due to coding particulars, the price change that results from a change in quantity supplied is shifted forward by one time step as the notation above suggests. Also as the above equation suggests, very low or zero change in price can make the supply elasticity extremely high or undefined, respectively. This issue is resolved in the code by setting supply elasticity equal to last year’s elasticity when the absolute value of a year-to-year price change is less than $0.10.

Another response metric is sustainability. Frameworks with which to assess sustainability include “social, economic, environmental” (SEE), “benefits, costs, risks, opportunities” (BCOR), “strengths, weaknesses, opportunities, threats” (SWOT), “(driving force), pressure, state, (impact), response” (D)PS(I)R, and “greenhouse gas balance,
competition for land, biodiversity, economic prosperity, social well-being, environment” (Buchholz, Luzadis, & Volk, 2009). A survey of experts finds SEE to be the preferred framework, with (D)PS(I)R the second most preferred (Buchholz, Luzadis, & Volk, 2009). Greenhouse gas balance, energy balance, and soil protection are the top three concerns among the most critical markers of sustainability, according to experts (Buchholz, Luzadis, & Volk, 2009). While greenhouse gas balance is beyond the scope of FABLE, since the model makes no assumptions on what happens to harvested timber, FABLE can determine whether decision criteria and market forces cause a net decrease in the stock of biomass, thus determining whether the aggregate behavior results in a net carbon sink or source in the long run. This sustainability index is calculated as the ratio of current aggregate inventory (standing forest) to the average possible inventory with no harvest (in the model, 4,199,972 green tons). To address the economic aspects of sustainability, simulations which include years where no income is earned are considered unsustainable (as it turns out, every year generates income in the present study, so this feature is omitted from the analysis).

Price is another important metric that gauges the aggregate market behavior of agents. Price is initialized as the price0 parameter previously discussed. This parameter is updated at each time step as a variable according to the minimum bid that results in total demand being met. Given the known change in price, current demand and assumed demand elasticity, the next time step’s demand is calculated using the demand elasticity function solved for final demand:

\[ Q_{j+1} = E_D Q_j \left( \frac{P_{j+2} - P_{j+1}}{P_{j+1}} \right) + Q_j \]
Average harvest age for each case is the final response metric. Average harvest age highlights the stability or evolution of optimal harvest age due to market conditions and underlying decision and inventory processes.

Processing

The “Behavior Space” function in Netlogo allows parameter values to be changed for consecutive model runs. Behavior Space then exports the resulting response metrics from all runs as a Microsoft Excel sheet. These data are then available to produce graphs which are a convenient mode for displaying results.

Concise Statement of Assumptions, Inputs and Outputs

To summarize, FABLE makes assumptions about parameters, demand, market processes, biological processes and landowner behavior. These assumptions and processes are inputs to the model, and model outputs include supply elasticity, sustainability index, price, average harvest age, removals, demand, and inventory. These elements of the model are summarized below (Table 1).
Table 1. Assumptions, Inputs and Outputs of Forest Agent-Based Landowner Economy Model.

<table>
<thead>
<tr>
<th>Inputs/Parameter Assumptions</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Demand level: {8, 10, 12, 14, 16, 18, 20}</td>
<td>• Supply elasticity</td>
</tr>
<tr>
<td>• Demand elasticity: -0.5</td>
<td>• Sustainability index</td>
</tr>
<tr>
<td>• Real interest rate: ranging from 3% to 7%</td>
<td>• Inventory</td>
</tr>
<tr>
<td>• Initial price: $30/green ton (divide all prices by $30 to index the price)</td>
<td>• Price</td>
</tr>
<tr>
<td>• Initial age distribution: \sim N(45,15^2)</td>
<td>• Average harvest age</td>
</tr>
<tr>
<td>• Transportation cost parameter (or average cost to import): $10/green ton</td>
<td>• Removals</td>
</tr>
<tr>
<td>• Price floor: $10/green ton</td>
<td>• Demand</td>
</tr>
<tr>
<td>• Growth function: deterministic, empirical</td>
<td>• Age class histograms</td>
</tr>
<tr>
<td>• Landowner decisions: (1) reservation price Faustmann, (2) reservation price Hartman, (3) fixed rotation Faustmann</td>
<td>• Average real discount rate of landowners that harvest in a given year</td>
</tr>
<tr>
<td>• Hartman (amenity) parameter: $0.75</td>
<td></td>
</tr>
<tr>
<td>• Auction: private value auction with a single iteration, agents bid every year based on last year’s price</td>
<td></td>
</tr>
<tr>
<td>• Plots/Acreage: 4225 quarter-acre plots for a total of 1056.25 acres.</td>
<td></td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

FABLE generated data for 35 model runs total and 7 runs of varying demand levels (even numbers between 8 and 20, inclusive) each for the five cases. Demand level denotes an initial demand in 10 thousand green tons that corresponds to the initial price of $30. Each run is a simulation lasting from 2010 to 2310. For each year, FABLE reports eight items: supply elasticity, sustainability index, price, average harvest age, removals, demand, inventory, and age class histograms. Unless otherwise noted, all figures generated from these data use time (calendar year) as the independent variable.

Inventory

FABLE generates aggregate inventory by summing the amount of green tons on all stands. The reservation price Faustmann case shows that a higher demand level leads to a lower inventory at the first minimum (Figure 4). However a high demand level like 20 (18 and 16 as well) result in a rebound in inventory above those of lower demand levels. In the long run, regardless of demand level, the reservation price Faustmann case’s inventory oscillates about 1.75 million green tons.
Inventory for the fixed rotation Faustmann case is less complicated. Demand level does not affect inventory, and short term behavior is not quantitatively or qualitatively different than long term behavior, except for the initial liquidation of stands overdue for harvest (Figure 5). Inventory averages to 1.3 million green tons over the entire model run.

Figure 5. Inventory for fixed rotation Faustmann by demand level.
In the reservation price Hartman case, a lower demand level corresponds to an earlier first minimum in inventory (Figure 6). Furthermore, the first minimum that occurs is an absolute minimum for the entire run. Higher demand level is also associated with lower inventory in the long run, ranging from 2.1 to 3 million green tons for demand levels 20 and 8, respectively.

![Figure 6. Inventory for reservation price Hartman by demand level.](image)

The majority Faustmann (Figure 7) and majority Hartman (Figure 8) cases show less variation by demand level than the reservation price Hartman case. Also the curves representing inventories for the mixed cases are less smooth than the pure cases. However, the former shares the long run convergence of inventories exhibited by reservation price Faustmann. In contrast, the majority Hartman case exhibits divergent inventories in the long run, differentiated by demand level in the same manner as reservation price Hartman.
Figure 7. Inventory for reservation price Faustmann (66\%) and reservation price Hartman (34\%) by demand level.

Figure 8. Inventory for reservation price Faustmann (34\%) and reservation price Hartman (66\%) by demand level.

The differences among cases described above are visible when results for each case are plotted in a single figure (Figure 9). The demand level is 14 in this comparison.
Figure 9. **Inventory for all five cases at demand level 14.**

**Removals**

For all cases except fixed rotation Faustmann, the overarching narrative for removals is the same in the first few decades—removals remain relatively constant at (or slightly higher than) the initial demand level. Then removals meet a tipping point, where removals shift depending on demand level. Again, in all cases except fixed rotation Faustmann, demand level 20 is the first to reach this point of change.

The fixed rotation Faustmann case (Figure 10) shows an initial spike in removals that occurs when the initial distribution of stand ages results in stands being overdue for optimum harvest. Beyond this initial outlier event, subsequent years for the entire model run show baseline removals of 20 thousand green tons and occasional spikes of up to a several additional 100 thousand green tons.
Figure 10. *Removals for fixed rotation Faustmann by demand level.*

For the reservation price Faustmann case (Figure 11), removals at all demand levels converge to an average of approximately 140 million green tons in the long run. However, removals for demand level 20 drop lower than even demand level 8 on the path to long run convergence. Also notable is the volatility in removals for demand level 20 between 2045 and 2052. This is caused by the transportation cost parameter being triggered. In the years where the sharp drop in removals occurs, agents attempted to cast bids that were more than $10 per green ton above last year’s price (some agents casted bids within the constraints, resulting in the 40,000 green tons shown in year 2045). In these years, the remainder of demand is presumed to be met by importing from elsewhere.
Long term removals for the reservation price Hartman case (Figure 12) are higher for a higher demand level. The paths to the long term trend are smooth and without oscillation. Unlike the reservation price Faustmann case, removals for demand level 8 decrease in the long run. In the long run, removals range from 80 to 135 thousand green tons for demand level 8 and 20, respectively. In the year 2033, demand level 20 triggers the transportation cost parameter in the same manner described above for reservation price Faustmann.
Figure 12. Removals for reservation price Hartman by demand level.

Both mixed cases resemble the reservation price Hartman case most. However, the majority reservation price Faustmann case (Figure 13) shows a long term trend of increasing removals. The distinction by demand level is smaller for the majority Faustmann case, ranging from 110 to 135 thousand green tons for demand level 8 and 20, respectively. The majority Faustmann case also shows dips in removals similar to the reservation price Faustmann case. Removals in the majority Hartman case (Figure 14) range from 95 to 140 thousand green tons for demand level 8 and 20 in the long run, respectively. A single plot of all cases for demand level 14 demonstrates the similarities and differences mentioned above (Figure 15). For the sake of readability, removals for the fixed rotation Faustmann case are allowed to lie outside of the plot area.
Figure 13. Removals for reservation price Faustmann (66%) and reservation price Hartman (34%) by demand level.

Figure 14. Removals for reservation price Faustmann (34%) and reservation price Hartman (66%) by demand level.
Supply Elasticity

Recall that fixed rotation Faustmann landowners do not change their behavior according to price, whereas reservation price Faustmann landowners do. For each case except fixed rotation Faustmann, measured supply elasticities are volatile, but a majority of measurements lie within the range 0 to 1. Higher demand level tends to be associated with more frequent price changes. A higher frequency in price changes creates more successful measurements. The reservation price Faustmann case (Figure 16) obtained the most data points because it produced a price change more often than the other cases. For the reservation price Faustmann case, the mean supply elasticity for the entire model run was 0.51, 0.50 and 0.40 for demand levels 8, 14 and 20, respectively. The number of data points for reservation price Hartman (Figure 17) is less than reservation price Faustmann. In this case, the mean supply elasticity for the entire model run was (0.21), 0.48 and 0.39 for demand levels 8, 14 and 20, respectively (the demand level 8 mean derives from only 7 successful
measurements). The mixed cases mimic the disparity in data between reservation price Faustmann and reservation price Hartman; the case with more Faustmann has more observations (Figure 18), and the case with more reservation price Hartman has fewer observations (Figure 19). In the majority reservation price Faustmann case, the mean supply elasticity for demand level 8 was 1.29, however, controlling for two outliers (supply elasticities equal to 122 and 94) gives a supply elasticity of (0.15). For demand levels 14 and 20 in the majority reservation price Faustmann case, the mean supply elasticities are 0.28 and 0.45, respectively. In the majority reservation price Hartman case, the mean supply elasticity for the entire model run was 0.34, 0.36 and 0.41 for demand levels 8, 14 and 20, respectively.

The fixed rotation Faustmann case (Figure 20) contains few actual data points because in each case, regardless of demand level, prices precipitously drop to the minimum allowed by the model. Still, the mean price elasticities are 0.23, (1.45) and (0.82), for demand levels 8, 14 and 20, respectively.

Figure 16. Supply elasticity for reservation price Faustmann by demand level. Note: Flat behavior indicates years in which supply elasticity could not be measured due to no price change or other factors.
Figure 17. Supply elasticity for reservation price Hartman at by demand level. Note: Flat behavior indicates years in which supply elasticity could not be measured due to no price change or other factors.

Figure 18. Supply elasticity for reservation price Faustmann (66%) and reservation price Hartman (34%) at a medium demand level (14). Note: Flat behavior indicates years in which supply elasticity could not be measured due to no price change or other factors.
Figure 19. Supply elasticity for reservation price Faustmann (34%) and reservation price Hartman (66%) at a medium demand level (14). Note: Flat behavior indicates years in which supply elasticity could not be measured due to no price change or other factors.

Figure 20. Supply elasticity for fixed rotation Faustmann at a medium demand level (14). Note: Flat behavior indicates years in which supply elasticity could not be measured due to no price change or other factors.

**Sustainability Index**

Sustainability index is related to forest inventory. It is the ratio of inventory in a given year to the average inventory in the model when no harvests occur (without harvests, inventory oscillates due to growth and natural deaths). For the reservation price Faustmann
case (Figure 21), demand level affects the sustainability index in the beginning in an intuitive manner. A higher initial demand level causes a faster depletion of forest stock. But at the higher demand levels 18 and 20, the forest rebounds to a higher sustainability index. However, in the long run, regardless of demand level, the sustainability index stabilizes, oscillating near 0.45 regardless of demand level.

Figure 21. *Sustainability index for reservation price Faustmann by demand level.*

In contrast, fixed rotation Faustmann shows overlapping sustainability indexes for all cases regardless of demand level (Figure 22). This result is not surprising since fixed rotation Faustmann landowners harvest according to stand age, not price or demand level, and the initial distribution of stand ages and interest rates is independent of demand level. The average sustainability index for fixed rotation Faustmann is approximately 0.325.
The reservation price Hartman case follows the logic that greater demand level means a lower sustainability index, but unlike the other pure cases, this correspondence holds in the long run. At demand levels (8, 10, 12, 14, 16, 18, 20) the long run sustainability index is approximately (0.75, 0.72, 0.61, 0.60, 0.55, 0.54, 0.53), respectively (Figure 23). Another feature is that the highest and lowest demand levels lead to more oscillatory long run behavior of the sustainability index than the medium demand levels. Whereas the demand level 8 case oscillates due to the fact that harvests are masked behind the natural growth and death cycle of the forest, the demand level 20 oscillates due to “ripple effects” from the large initial demand. High initial demand level is thus akin to a perturbation in the stock of a forest.

Figure 22. *Sustainability index for fixed rotation Faustmann by demand level.*
The two mixed cases exhibit characteristics of both the reservation price Faustmann and reservation price Hartman, having oscillatory behavior and an inverse relationship between sustainability index and demand level in the long run, respectively. However, the case with a greater percentage of reservation price Hartman landowners (Figure 24) has a wider range in long run sustainability index than the case with a greater percentage of reservation price Faustmann (Figure 25). In the former, sustainability index ranges between 0.48 and 0.69, whereas the latter ranges between 0.45 and 0.59. Across cases, the trend is that a higher reservation price Hartman percentage leads to a wider range in long run sustainability index values and increases the maximum potential sustainability index that occurs with a lower demand level. The demand level 14 case provides for a comparison (Figure 26).
Figure 24. *Sustainability index for reservation price Faustmann (34%) and reservation price Hartman (66%) by demand level.*

Figure 25. *Sustainability index for reservation price Faustmann (66%) and reservation price Hartman (34%) by demand level.*
Figure 26. *Sustainability index for all cases at demand level 14.*

**Price**

For the fixed rotation Faustmann case prices decrease to the minimum allowed by the model, and once the minimum price occurs, that price holds for every year in the future (Figure 27). This is consistent with fixed rotation Faustmann behavior. Since landowners will harvest based only on age, they are willing to take any price. The rate of price decrease appears to have no discernible correlation to demand level.
Figure 27. *Price for fixed rotation Faustmann by demand level.*

The other four cases reveal a separate phenomenon, a “price bubble effect” (Figure 28). This phenomenon is characterized by a rapid increase in price, followed by a rapid drop. At demand level 20, price remains higher after the price bubble than before.
“Price bubble” effect demonstrated at demand level 20 for four cases: reservation price Hartman (Hartman-R), majority reservation price Hartman (Hartman 66%), majority reservation price Faustmann (Faustmann 66%), reservation price Faustmann (Faustmann-R). Fixed rotation Faustmann is not included in this figure because it does not exhibit a price bubble effect.

For the reservation price Faustmann case, a price bubble occurs for demand levels greater than 14 (Figure 29). For the majority reservation price Faustmann mixed case, the price bubble occurs for demand levels greater than 12 (Figure 30). For the reservation price Hartman and majority reservation price Hartman mixed case (Figure 31 and Figure 32, respectively), a price bubble occurs at all demand levels. For all of the four cases, the size of the price bubble is nonlinear with respect to demand level. For example, in the reservation price Hartman case, the price bubble peaks at $181 for demand level 20 but peaks at $90, $55 and $41 for demand levels 18, 16 and 14, respectively.
Figure 29. Price for reservation price Faustmann by demand level.

Figure 30. Price for reservation price Faustmann (66%) and reservation price Hartman (34%) by demand level.
Figure 31. *Price for reservation price Hartman by demand level.*

Figure 32. *Price for reservation price Faustmann (34%) and reservation price Hartman (66%) by demand level.*
The year in which the peak of the price bubble occurs is differentiated most visibly in the reservation price Faustmann case. Higher demand level in the reservation price Faustmann case leads to an earlier bubble. For example, the peak occurs in (2064, 2072, 2078) for demand level (20, 18, 16), respectively. The reservation price Faustmann case exhibits oscillations in price not as prominent in other cases. In addition, the amplitude of the oscillation increases with increasing demand level (Table 2). In contrast, for the reservation price Hartman case the peaks occur in 2073 and 2078 and circa 2062 for demand levels 20 and 18, respectively. At the lower demand levels for all those cases including reservation price Hartman landowners, the peaks are characterized by several consecutive years where price changes little to no amount. A greater percentage of reservation price Hartman is associated with a later peak in price for demand level 20 (2071 for the majority reservation price Hartman case and 2063 for the majority reservation price Faustmann case). For the majority Hartman and majority Faustmann cases, respectively, the peak for demand level 18 occurs in 2077 and 2068 for demand level 20.

Table 2. Amplitude of long term price oscillations for reservation price Faustmann by demand level.

<table>
<thead>
<tr>
<th>Demand Level</th>
<th>High Long Term Price ($ / Green Ton)</th>
<th>Low Long Term Price ($ / Green Ton)</th>
<th>Amplitude of Long Term Price Oscillation ($ / Green Ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>10.00</td>
<td>10.00</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>17.21</td>
<td>12.09</td>
<td>5.12</td>
</tr>
<tr>
<td>12</td>
<td>26.75</td>
<td>18.38</td>
<td>8.36</td>
</tr>
<tr>
<td>14</td>
<td>33.48</td>
<td>24.95</td>
<td>8.53</td>
</tr>
<tr>
<td>16</td>
<td>40.37</td>
<td>37.42</td>
<td>2.94</td>
</tr>
<tr>
<td>18</td>
<td>49.51</td>
<td>42.71</td>
<td>6.80</td>
</tr>
<tr>
<td>20</td>
<td>72.05</td>
<td>53.33</td>
<td>18.72</td>
</tr>
</tbody>
</table>
In contrast to the reservation price Faustmann case, all cases which include some percentage of reservation price Hartman show no oscillation in the long run. The long term trends for every case except fixed rotation Faustmann show a higher long term price corresponding to a higher demand level (Figure 33). Higher demand level also leads to a slight downward price trend in the long run, whereas long term price trends associated with lower demand levels are relatively flat.

Figure 33. Price for reservation price Faustmann (34%) and reservation price Hartman (66%) by demand level.
Average Harvest Age

For all cases an average harvest age bubble occurs that is analogous to the price bubbles. The bubble that occurs for fixed rotation Faustmann happens in a single year, the first year, with all landowners randomly assigned a harvest age above their optimum choosing to harvest (Figure 34). Beyond the initial year, the fixed rotation Faustmann case shows an average harvest age around 24 with some year-to-year variability.

Figure 34. Harvest age for fixed rotation Faustmann by demand level.

The harvest age bubbles for the other cases reach more extreme ages and occur over as much as a decade (Figure 35). The end of the harvest age bubbles, characterized by a precipitous drop in average harvest age, coincides with the beginning of the price bubble (Figure 36). A higher demand level corresponds to a larger drop in average harvest age.
Figure 35. Harvest age bubble effect demonstrated at demand level 20 for four cases: reservation price Faustmann (Faustmann-R), reservation price Hartman (Hartman-R), majority reservation price Faustmann (Faustmann 66%), majority reservation price Hartman (Hartman 66%). Fixed rotation Faustmann is not included in this figure because it does not exhibit this effect.

Figure 36. Harvest age and price bubbles at demand level 20 for reservation price Hartman.
In the long run, average harvest age exhibits other features. For the reservation price Faustmann case, average harvest age oscillates around 30 in the long run regardless of demand level (Figure 37). However, for demand level 20, a particularly interesting anomaly occurs. As observed previously from the removals plot (Figure 10), a sharp drop in harvest occurs in the years between 2045 and 2052 because price increases cause imports from another region (landowners’ bids exceed last year’s price plus the $10 per green ton transportation premium). As a result, average harvest age spikes in years between 2100 and 2140 when those stands previously not harvested are harvested at a greater age.

![Figure 37. Harvest age for reservation price Faustmann by demand level.](image)

Unlike the reservation price Faustmann case, the reservation price Hartman case does not converge to a single average harvest age in the long run. Instead, lower demand levels
correspond to higher average harvest age. Whereas demand level 8 corresponds to long run average harvest age around 38 and remains relatively stable, demand level 20 corresponds to a long run average harvest age of 30 at its lowest but shows volatile spikes up to 50 on a periodic basis (Figure 38). Demand level 10 through 14 appear volatile, ranging in value between approximately 30 and 50 (Figure 39).

Figure 38. *Harvest age for reservation price Hartman for demand levels 8 and 20.*
Figure 39. Harvest age for reservation price Hartman for demand levels 10 and 14.

Finally, demand levels 16 and 18 are very similar to demand level 20, having a baseline of 30 and volatile upward spikes in the long run (Figure 40).
The long term behavior in average harvest age for the mixed cases is convergent like the reservation price Faustmann case, but a higher percentage of reservation price Hartman landowners increases the difference by demand level. For the majority Faustmann case, there is very little distinction between demand levels 8 and 20 (Figure 41). For the majority Hartman case (Figure 42), demand levels 8 and 20 differ in terms of volatility, and no periodic pattern appears to emerge. When all cases are compared at demand level 14, the general long run trend is that average harvest age is positively correlated to a higher percentage of reservation price Hartman landowners (Figure 43).
Figure 41. Harvest age for reservation price Faustmann (66%) and reservation price Hartman (34%) by demand level.

Figure 42. Harvest age for reservation price Faustmann (34%) and reservation price Hartman (66%) by demand level.
Figure 43. Harvest age for all cases at demand level 14.

Age Class Histograms

Histograms of age classes of inventory can enrich the understanding of the average harvest age dynamics. As FABLE initializes, all cases start with a normally distributed age class structure (Figure 44). A similar situation arises in the years 2020 to 2040 in all cases except fixed rotation Faustmann, as demonstrated by the age class distribution of the reservation price Faustmann case at demand level 14. In 2020 (Figure 45), young- and medium-aged trees are depleted, leaving only older trees to harvest. By 2040 (Figure 46), most of the old have either been harvested or have died naturally.
Figure 44. *Beginning age class distribution for all cases.*

Figure 45. *Age class distribution for reservation price Faustmann in 2020 at demand level 14. Excluding the fixed rotation Faustmann case, other cases are similar.*
Figure 46. Age class distribution for reservation price Faustmann in 2040 at demand level 14. Excluding the fixed rotation Faustmann case, other cases are similar.

In 2064, the observed price bubble effect at demand level 20 begins to peak for the reservation price Faustmann case. The age class distribution at this point has no trees above age 40, and has the highest inventory in the “21 to 30” age class (Figure 47).
Figure 47. Age class distribution for reservation price Faustmann in 2064 at demand level 20. Excluding the fixed rotation Faustmann case, other cases are similar at their respective price bubble peak.

The decline in price that follows the price bubble peak (as in year 2080) is associated with a more evenly distributed age class structure, having trees in age classes up to the “41 to 50” class (Figure 48). By this time, demand has adjusted and stabilized (as seen in the removal plots) to a level that allows more age classes to be filled.
Figure 48. Age class distribution for reservation price Faustmann in 2080 at demand level 20. Excluding the fixed rotation Faustmann case, other cases are similar at their respective price decrease following the price bubble peak.

In the long run (2250), the reservation price Faustman case in demand level 20 shows the most even-aged distribution throughout the run, with no trees beyond the average harvest age (Figure 49).
Figure 49. Age class distribution for reservation price Faustmann in 2080 at demand level 20. Excluding the fixed rotation Faustmann case, other cases are similar in the long run, except reservation price Hartman percentage generally increases the frequency in higher age classes.

**Summary Supply Curves**

Supply curves for the cases excepting fixed rotation Faustmann can offer a holistic view of the aggregate behavior. The quantity supplied is a function of price, inventory and demand level. However, the cases are dynamic and thus need to be converted to a static analysis. The years 2020, 2060 and 2250 provide representative snapshots of three key periods in these cases. Respectively, these years represent the harvest age bubble, price bubble and long term stability in prices. Constructing a supply curve consists of obtaining the (quantity, price) coordinate for every demand level and plotting them in price-quantity space.
Supply curves in the year 2020 (Figure 50) are elastic due to an abundance of high yield stands and the resulting negligible price changes. This is not a typical observation in empirical studies, but empirical studies tend to observe established markets. In contrast, the initial years in FABLE are more representative of an old-growth forest. At this point, the market has not yet “discovered” a limit to sustaining the current level of removals indefinitely. The level of removals is determined by the demand curve. Recalling that the demand curves established separate quantities (80,000 to 200,000 green tons) that correspond to the same price level ($30/green ton), one interpretation is that the elastic supply is simply a remnant of the initial conditions (recall Figure 1). But we know that given the same initial inventories, not every initial condition, a (price, quantity) pair, could be consistent with equilibrium. Thus, this supply curve could also be interpreted as a supply curve during disequilibrium. A real-world analog to this situation might be found in a government policy that requires a quota at a certain price (perhaps, a renewable fuel standard that mandates a certain quantity of fuel to come from wood).
Contrasting with the 2020 case, near the peak of the price bubble event in year 2060 (Figure 51), a backward-bending supply curve appears. The negative sloping portion of this supply curve occurs when costs or interest rates are high (Binkley, 1993). In these cases, high costs and interest rates are indeed a likely cause. The price bubble begins when the “supply” of low bidding agents has been exhausted and a greater number of high bidding agents cast winning bids. Participants in the market at this time have higher “psychic” costs due to their reservation price behavior. So the backward-bending supply curve is preceded by high costs. When the price bubble peaks, agents with high discount interest rates cast winning bids.

Figure 50. Supply curves for four cases in the year 2020.
Agents with high discount rates are likely to cast lower bids because they place lower value on future growth. This is consistent with the bubble “bursting.”

Figure 51. Supply curves for four cases in the year 2060.
Figure 52. Average discount rate of successful bidders at demand levels 8 and 20 for the majority reservation price Faustmann case. High interest rates in the shaded region correspond to the price bubble and the supply curve presented in Figure 50.

In 2250 (Figure 53) prices have fallen into a more stable pattern. Supply curves during this time exhibit inelastic behavior typical of forest markets. Percentage of reservation price Hartman agents is positively associated with a less inelastic supply curve than percentage of reservation price Faustmann agents.
Implications of Different Assumptions

The results examined thus far have relied on simplifying assumptions that were necessary to isolate the effects of heterogeneous agent decisions on forests and forest markets. In the analysis that follows, a few of these assumptions are relaxed to determine the sensitivity of the price results on the assumptions. The makeup of agents in these adaptations is 66 percent reservation price Faustmann and 34 percent reservation price Hartman. However, the decision processes are not precisely the same as reservation price decisions in the “variable reservation price” and “emergency harvest” case.
**FABLE with Heterogeneous Growth Functions**

In order to consider the effects of environmental noise and differential growth rates among trees, growth functions were multiplied by a coefficient consisting of a normal distribution centered at 1 with a standard deviation of 0.3 plus a randomly generated percentage between 0 and 50 percent. The results primarily show that heterogeneous growth functions reduce the size of the price bubble effect (Figure 54). Secondly, price curves are less smooth than in previous cases. This result suggests that fewer agents are participating in the market and those agents that do participate have faster growing (more productive) trees and bid lower.

![Figure 54. Price with heterogeneous growth functions for the majority reservation price Faustmann case by demand level.](attachment:figure54.png)
Another sensitivity test consists of variable reservation prices, where agents make imperfect calculations in the following manner: (1) Each agent discounts future values according to their agent type (reservation price Faustmann or reservation price Hartman). (2) The agent’s maximum bid derived from this calculation is multiplied by a normal distribution centered at 1 with a standard deviation of 0.1. The net effect is that agents bid near their ideal (according to the calculation) bid, but may overbid or underbid. The results show that highly oscillatory behavior results and higher amplitudes are associated with a higher demand level (Figure 55). This effect occurs because bidding errors cause a decrease in the average harvest age. At high demand levels, lower average harvest age continuously recreates the inventory conditions that caused the price bubbles in the FABLE runs without variable reservation prices.
Figure 55. Price with variable reservation price calculations for the majority reservation price Faustmann case by demand level.

**FABLE with Emergency Harvests**

To simulate cases where landowners might harvest under an emergency situation, and hence bid very low, each stand is given a random probability for emergency. When an emergency happens, agents bid $10 per green ton, the price floor, in order to ensure they have an opportunity to sell. Agents do not account for the risk of an emergency in the future, but instead react to an emergency as it happens. Simulations were run for demand level 20 and 14 for the majority reservation price Faustmann case.
For demand level 20 (Figure 56), cases with an emergency probability greater than 3%, prices drop to the price floor after the price bubble peak and enter a new paradigm of oscillating and low prices. This cycle perpetuates itself because agents do not remember higher prices, and year-to-year price increases are limited to $10 per green ton. In the case of demand level 14 (Figure 57), similar oscillations occur for emergency probability greater than or equal to 3%, but the frequency is much lower due to a lower demand level.

Figure 56. Price for demand level 20 of the emergency harvest/majority reservation price Faustmann case by percent chance of an emergency occurring for each stand.
Figure 57. Price for demand level 14 of the emergency harvest/majority reservation price Faustmann case by percent chance of an emergency occurring for each stand.

**FABLE with Higher Hartman Parameters**

Sensitivity on the Hartman parameter (the factor that places value on a standing forest in proportion to the square of stand age) is examined by letting the parameter take on values 0.75 (the original value), 1.5, 2.5, 4, 10, 25 and 100. In the demand level 14 case (Figure 58), increasing the Hartman parameter enhances the size of the price bubble in a similar way that increasing demand level does and also raises to long term price. However, increasing the Hartman parameter even to 100 only raises the peak price to $150 per green ton. The reason this parameter does not change the price peak more substantially is that at the peak, inventory
is overall very young and future values where the Hartman parameter is active are discounted.

In the demand level 20 case (Figure 59), increasing the Hartman parameter does even less to the peak price, demonstrating in a more extreme manner that younger inventories diminish the effect of the Hartman parameter. Also an interesting feature is the fact that when the Hartman parameter is 25, the price peak is greater than the price peak that occurs when the Hartman parameter is 100. This happens because the transportation cost constraint is triggered more often with the latter (wood is imported from other regions), and wood that is not harvested in these years increases the overall inventory in the case when the Hartman parameter is 100.

Figure 58. Price for demand level 14 of the majority reservation price Faustmann case by Hartman parameter value.

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CONCLUSION

The Forest Agent-Based Landowner Economy model generates inventory, removals and prices from a market simulation using forest landowner agents. The results of three agent types in five cases with seven initial demand levels reveal interesting observations about the aggregate implications of theoretical forest landowner behavior.

First, FABLE shows that in the case of all landowners harvesting according to a fixed Faustmann rotation, prices fall to the minimum allowed by the model. The real world analog of this model constraint is cost. Thus, a FABLE simulation shows that a world with all fixed rotation Faustmann landowners is one without profit for landowners. One caveat is that the model assumes no price impact resulting from surpluses or shortages inherent in the fixed
rotation Faustmann case. However, because harvests are not responsive to market conditions
in the fixed rotation Faustmann case, an arbitrary mechanism for dealing with surpluses’ or
shortages’ impact on prices would perhaps not increase realism. A second caveat is that the
observed behavior for the fixed rotation Faustmann case is explicitly dependent on the
bidding assumptions. In the current case, the assumption was that agents would bid last
year’s price or lower because the agents are going to harvest regardless of market price. They
effectively harvest first and then find out what price they will get. Such behavior is consistent
with decreasing prices, but it may be entirely futile to use a market simulation to describe this
behavior. In fact, this case’s anomalous results are in agreement with literature which asserts
that landowners do not really behave like fixed rotation Faustmann landowners (Norstrom,
1975; Hartman, 1976; Routledge, 1980; Koskela, 1989; Pukkala & Kanga, 1996; Zhang,
2001).

The reservation price Faustmann case is unique for two major reasons. For one,
through the aggregating mechanism of a simulated market, reservation price Faustmann
achieves long term stability in inventory, removals and sustainability index regardless of
initial condition (demand level). Prices, though, are path dependent; a higher demand level
results in a higher long term price. Secondly, reservation price Faustmann shows the most
oscillation of output variables among cases. Average harvest age, inventory, removals and
price all manifest this behavior. Oscillatory behavior is attributable to the absence of placing
value on a standing forest, since this behavior is slightly observable in the majority
Faustmann mixed case and not observable in the majority Hartman mixed case.
In contrast to reservation price Faustmann, the reservation price Hartman case is typified by a correspondence between demand level and long term trends. Higher demand level means higher long run prices and removals and lower long run inventories, sustainability indices and average harvest ages. Furthermore, for the mixed cases, a higher percentage of reservation price Hartman increases the difference between long term demand level effects. The reservation price Hartman decision places value on a standing forest, and the results from FABLE show that the aggregate effect in general is a higher sustainability index than other cases. In particular, even demand level 20 for the reservation price Hartman case results in a higher sustainability index than demand level 8 for the reservation price Faustmann case.

Other prominent market features of the results are the price and harvest age bubbles that occur in all cases except fixed rotation Faustmann. These occur for a few reasons. Due to the bidding process, those agents with low interest rates win bids in the early years. Furthermore, early on those agents with older stands contribute to demand being met with a smaller number of total agents, causing average harvest age to rise. When older stands become fewer in number, a greater number of agents with a smaller inventory participate in meeting demand, causing the price bubbles and the dramatic drop in average harvest age.

Price bubbles in real forest markets happen when supply or demand shocks occur or during a phase of speculation. For example, Prestemon and Holmes show that a hurricane can cause a sharp price drop due to salvage, followed by a price increase above what would have occurred otherwise (Prestemon & Holmes, 2000). Another example is a price bubble in Douglas fir that occurred in the American Northwest in the early 1980’s (Mattey, 1990). The
price bubble arguably occurred due to speculation on government contracts, but a more subtle explanation is that bidders “interpreted available economic information in a way that rationalized their choice to gamble on the contracts” (Mattey, 1990). The price bubbles produced by FABLE result from a supply shock, as demonstrated by the diminished inventory that precedes the bubble. However, the price bubbles exhibited by FABLE share with a speculative bubble the fact that price increases are in part related to the beliefs of agents.

As proposed in the introduction, the results of FABLE contrast most with econometric methods. First, price bubbles are not consistent with standard econometrics models, and econometric methods have difficulty detecting bubbles (Gurkaynak, 2008). In contrast, FABLE readily produces bubbles under market conditions of high demand and low supply. Both econometric methods and FABLE assume basic features of economics, that markets work and supply meets demand. The market in FABLE adjusts until the demand and price correspond to a feasible supply. The adjustment time period is endogenous to decision-making and biological assumptions and is not directly controlled. Econometric methods, on the other hand, may assume that reaching equilibrium takes time, but usually this assumption requires an explicit change to the econometric model. Furthermore, FABLE simulates a market from the bottom up, with agents (firms) explicitly bidding based on last year’s price. An econometric approach might use last year’s price in a more direct manner. Both methods rely on assumptions about individual behavior. Econometrics generally assumes that individuals are rational and employs a representative agent assumption. FABLE assumes that individuals are rational but that different rational objectives can have important consequences.
to the macroeconomic behavior. The results of this study provide theoretical evidence that supports the importance of heterogeneity.

Two of the supply curves reveal aggregate behavior similar to that in the literature—the backward-bending supply curve resembles that of Binkley, and the long-term supply curve resembles inelastic supply curves typically found in empirical studies (Pattanayak, Murray, & Abt, 2002). On the other hand, the supply curve exhibited by the model in early years differs from the literature. When demand is extremely low relative to the forest stock, behavior is elastic. A reason for this difference might be that empirical studies require well-developed markets in order to have enough data to produce results, and the market in year 2020 of the model is not well-developed based on the price bubbles that follow. Another piece of evidence that supports the legitimacy of an elastic supply curve in year 2020 is that the average ratio of removals to inventory is 3.7%, whereas in the long run the average ratio of removals to inventory is 7.0%.

Areas for Improvement or Extension

FABLE contains a single product class most analogous to sawtimber. Expanding the model to include chip-n-saw and pulpwood was beyond the scope of this project. However, incorporating other product classes in future modeling efforts may lead to interesting dynamics.

The biophysical portion of FABLE is simple and does not take into account complex biogeochemical processes. However, given the diverse and uncertain growing patterns that arise from assorted climate differences and management choices, such a model would be
more complex. In the present study, a simple deterministic growth function allows FABLE to attribute differences in aggregate phenomena to heterogeneous decision-making features of agents. A first-order attempt at modeling heterogeneous growth functions shows that the effect may be to diminish the price bubble effect. Future models might connect GIS data and extensive tree growth research to an agent-based model to increase biophysical realism. For example, a model might simulate erosion due to intensive harvesting or the effects of adhering to forest certification standards, which may lead to changes in tree growth rates. Also, changes in management which might change tree growth rates are possible for inclusion.

Another area of improvement would be variable expectations in decision-making, where landowners can evaluate past actions and change course if they discover that their decision making process resulted in suboptimal outcomes. A first order study of the consequences of adding variability to rational bids showed the cyclical emergence of price bubbles. In another first order examination of emergency harvests, a higher risk of emergency produced price trends that hovered near the price floor due to liquidation. This situation is akin to an impending fire or hurricane risk that forces landowners to change their harvesting practices, or an individual financial emergency such as unemployment that causes a premature harvest. A related idea is the change in decision-making that may occur due to changing owners. Previous surveys determined that current forest landowners are over 60 years old on average (Majumdar, Teeter, & Butler, 2008). Landowners will eventually pass on land to an heir or otherwise sell land. Heirs will likely bring with them separate personal
values and experience and hence different ways of managing a forest. Agent-based modeling is capable of modeling this “bequest bubble.”

In FABLE, landowners interact with each other indirectly within a market. But in the real world, there may be sociological factors that increase the likelihood of harvest. For example, an influencing effect wherein a landowners inclination to harvest is related to a neighbor’s harvesting can be modeled.

Agent-based modeling is also equipped to incorporate networks, where landowners are not only influenced by neighbors, but also by acquaintances that live some distance away, by simulated media sources and by state extension offices.

The underlying model of behavior to be ascribed to agents is a key area for improvement. Agent-based modeling in this application is limited by our understanding of what motivates landowner behavior. The theoretical forest landowners used in this study were based on the literature. New landowner surveys might be developed that refine our understanding of landowner decision-making in a way that is useful for agent-based modeling. For example, does the landowner: make a Faustmann calculation, use a consultant forester for management decisions, or pay attention to prices on a regular basis? Having useful data on thought processes at the individual level would be conducive to modeling landowners in an agent-based framework and would generate the aggregate implications of empirical, as opposed to theoretical, landowner behavior.
REFERENCES


