Spring 5-8-2020

A Spatial Economic Model of Maine's Forest Product Industry: Interactions Between Markets, Policy, and Space

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A SPATIAL ECONOMIC MODEL OF MAINE'S FOREST PRODUCT INDUSTRY:

INTERACTIONS BEWTEEN MARKETS, POLICY, AND SPACE

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A DISSERTATION

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

(in Forest Resources)

The Graduate School

The University of Maine

May 2020

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An Abstract of the Dissertation Presented
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Recognizing the extensive historical and modern role of forests in Maine, this dissertation proposes a new dynamic-recursive, spatial allocation (DR.SAGE) model for examining Maine's forest economy to understand its continuing importance to the state. This model attempts to incorporate spatial elements into a general equilibrium framework to evaluate how shocks to the forest products markets, such as a large increase in exports each year, would ripple through Maine, where forest related goods are the primary export.

By adjusting previous estimates, contribution analyses for 2016 estimate that the forest products industry supports a $8.5B contribution to Maine. From here, it is projected that Maine's economy will grow just under 5% by 2025 with business as usual: a 5.3% increase in GDP and a 4.7% increase in annual harvests. Driven by inflation, prices will increase an average of 22.1% by 2025. During this time, some production moves into the central counties of York, Cumberland, Androscoggin, Kennebec, and Penobscot from the others.

Using the DR.SAGE model to analyze a spruce budworm infestation, I estimate that medium- and high intensity outbreaks will have long term consequences on the stock of softwood saw logs. I

also estimate that an external increase in the demands for forest products of 15.6% over nine years would increase most forest product sectors' outputs and prices by an additional 4%-10%; forest product sectors with proportionally large wood requirements and large export shares expanded the most. Despite this, Maine's GDP is estimated to grow only by an additional 0.1%-0.2%. Sectors which are not related to Maine's forest economy saw minimal decreases in price and output, while sectors competitive with forest sectors saw declines of 0.3%-0.6%.

Overall, the DR.SAGE model framework meets the project objectives: it provides details about harvest levels and locations for a variety of wood types; the stock of each wood types is grown endogenously in the model; it provides information about each broad sector's production in each county; and, it provides aggregate information about prices and county-level output for the forest product sectors.

ACKNOWLEDGEMENTS

I would like to thank my wife Eden Kalyanapu for moving to Maine with me so that I could pursue this opportunity and for endlessly supporting me along the way. I would also like to thank my committee members, particularly Mindy Crandall who taught me much more than research. I also owe thanks to the following grants, institutions, and people for making this work possible and improving my experience at the University of Maine:

- USDA ARS Forest Products and Utilization Award Agreement #58-0202-4-003
- NSF Sustainable Energy Pathways Award #1230908
- Maine Forest Products Council
- The State of Maine
- Craig Johnston
- Erin Simons-Legaard & Cen Chen
- Students of Nutting 223
- Aaron Weiskittel
- Megan Bailey
- Collaborations/Steve Shaler

Finally, I would like to thank my parents and sisters for getting me on the academic path and giving me many of the tools I needed to succeed.

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CHAPTER 1

INTRODUCTION

1.1. The Forestry Industry in Maine

In Maine, also known as the pine tree state, forest resources cover almost 90% of the land area (FIA Database, 2017). The most obvious forest resource, and the one given almost exclusive attention until the past few decades, is wood fiber in the form of trees. More recently however, research and management has begun to recognize activities such as ecotourism and carbon sequestration, among others, as forest ecosystem services.

The history of commercial forest product industries (FPI) in Maine is nearly 400 years long. All along the east coast, colonists arriving in the early 17th century found extensive forests filled with large, varied trees. This abundance and diversity led the settlers to heavily utilize wood and this nationwide reliance on wood fiber remained until after the Civil War (Bowyer et al., 2017). Many things made of metal or plastic today, from crates and barrels to tools and farm implements to railroad cars and parts, were still forest products through the 19th century (Sloane, 1963). Forest products have many variations but generally include all the things which are produced from forests, such as structural lumber, paper, biofuel, and wood for furniture (Henderson and Munn, 2013; Hughes, 2015; Joshi et al., 2013). An exhaustive list of forest resources and their subsequent products may be too long to even compile.

Due to Maine's remoteness and disputed control between England and France, settlement and commercial resource extraction in Maine began a few years later than more southern areas of New England, but the first sawmill in Maine was still constructed by 1634

(Cronin, 1983). In contrast to today, most of the land was not privately held but in the public domain, leading loggers to feel entitled to the trees they found. This created significant resentment when the English crown passed The Act of 1729, which reserved all large white pines not already on deeded land for royal naval shipbuilding. Still, the number of sawmills expanded rapidly to over 300 by 1840, mostly concentrated around the Bangor area and primarily processing pine and spruce (Cronin, 1983; Wood, 1935). This concentration led to Bangor's title as the Lumber Capital of the World from the mid to late 1800s. The expansion was fueled by the natural infrastructure of water in Maine, which provided cheap transportation through log drives down the Androscoggin, Kennebec, and Penobscot Rivers to supply the growing demand for lumber, both domestically and globally. Lumber was a leading export of the young United States, was needed for rapidly growing urban expansion in the Northeast, and was heavily demanded by a rising shipbuilding industry (Purvis, 1995; Purvis, 1999).

In the 1820's, around the time Maine gained statehood, dominance in the logging industry shifted from families and small partnerships to logging cooperatives primarily due to the need to coordinate large log drives (Wood, 1935). In the mid-19th century, when technology allowed wood pulp to be used to make paper in place of rags, demand for wood fiber experienced another surge. This coincided with the logging industry's moving from cooperatives to large, organized corporations (Smith, 1972). With the introduction of mixed rag and wood fiber paper by S.D. Warren in 1867, the Westbrook (Maine) mill became the largest paper mill in the world by 1880. This helped Maine became the largest pulp and paper producing state, a title held until the 1960s (Irland, 2009; Smith, 1970).

As the industry developed, there were innovations to support it. The Lombard Log Hauler (the first tracked vehicle), and the log peavey, still in use today in its modernized form, were both invented in Maine to support the industry. Today, paper and lumber still dominate forest products usage, but a broader perspective also recognizes the role that forests play in tourism, local recreation, climate regulation, and potential shifts back to bio-based energy (Bowyer et al., 2017; Crandall, Anderson, and Rubin, 2017). Currently, Maine's forest economy supports over 33,000 jobs directly and indirectly (Anderson III and Crandall, 2016). Historically, the use of the forest resource has been an integral part of the state's industrial identity and definition for the last 400 years, and economic analyses serve as important tools to understand the industry's current performance and importance to the state.

1.2. A Brief History of Modeling

During the Middle Ages, expanding towns and manufacturing placed heavy demands on European forests, leading to wood shortages. This depletion of forested areas created a need for forest inventory monitoring. Early inventories were primarily conducted independently by the concerned party. Towns or commercial enterprises would collect forest area and useable stock information for their own use and planning; these inventories were typically targeted towards specific end-uses. Such inventories served the interested parties well enough but varying methods and metrics meant no national inventories could be aggregated from the individuals (Zeng et al., 2015). These early plots were done either very thoroughly or relied on expert knowledge, but statistical advancements in the 19th century allowed for a shift to sampling methods. These methods made forest inventory collection a much less intensive process.

Formal government-organized inventories were introduced in many countries during the following century. Finland, Norway, and Sweden, with their heavily forested lands, were the first to implement national inventories in the 1910’s and 1920’s, followed by the United States in 1928. After World War II, many other countries followed, including Germany, France, Austria, China, and Switzerland (Zeng et al., 2015). Early national inventories employed strip sampling and then variable radius plots. As more resources became available and techniques were improved, most countries moved to fixed radius plots from detached field samples or in clusters (Zeng et al., 2015). These organized, large-scale inventories, supplemented by advances in the statistical sciences and computational power, greatly facilitated robust inventory modeling and forecasting. These inventory models and projections, in turn, allowed forest resources to explicitly enter in economic models.

The study of commercial and industrial use of Maine’s forest would be incomplete without including a dollars-and-cents economic perspective. This is where economic models play their role. The history of classical economic models is equally rich as inventory models, similarly, evolving its foundations over the last two and a half centuries and blossoming in the 20^{th} century. One of the earliest, postulated by Adam Smith in 1776, was the conceptual model of the invisible hand, which included the well know ideas of property rights, free markets, and self-interest. Other ideas still held in high regard today were developed over the next 40 years. Utility theory was presented by Jeremy Bentham in his 1789 *An Introduction to the Principles of Morals and Legislation*. David Ricardo proposed the ideas of comparative advantage as a key mechanism in free markets and that free markets create a tendency towards a steady state in the economy, or long-term equilibrium. An early economist named Jean-Baptiste Say had suggested a weaker form of short-run equilibrium a few years before, known as Say's Law. In 1848, heavily influenced by these preceding theories, and having been guided by Bentham himself, John Stuart Mill wrote a summary textbook on classical economics. Mill's *Principles of Political Economy* was used as a standard economics text for over 50 years (Robbins, 1998).

The following age of neoclassical economics established even more terms and ideas still used today. Prominent among these is the theory of marginal utility proposed by Jevons (1871), and developed by Menger (1871), Clark (1899), and Wieser (1914). The logic behind marginal utility and the concurrent increase in mathematical rigor in economic study together led to the first formulations of the theories of partial and general equilibrium models in 1871 and 1874, respectively. Partial equilibrium models, along with the idea of market failures caused by externalities, were largely emphasized in England and the United States, while general equilibrium was developed in Switzerland by Leon Walras and Vilfredo Pareto. Following World War II, these ideas were enhanced through increased mathematical rigor and computability. In the 1930's, econometrics (Frisch and Tinbergen), input-output modeling (Leontief), and linear programming (Kantorovich) were all developed, each topic resulting in a Nobel Prize in Economics. During the same decade, John Maynard Keynes formalized the idea of a demand driven economy and explained the role of both firm spending as well as government spending in driving aggregate demand while Harold Hotelling examined basic spatial and natural resource economic models (Robbins, 1998).

During the 1960's, Milton Friedman challenged Keynes' ideas on the government's role in managing the economy, preferring the idea of limited intervention through monetary policy and economic freedom as the path to both economic growth and social freedom. At the same time, Ronald Coase expounded on the role of property rights and trade in determining resource allocation, arguing that well defined rights and minimal transaction costs will always result in a consistent Pareto optimal resource allocation, regardless of who receives the initial property rights (Robbins, 1998). Before Hotelling, and even predominantly during his time, markets were abstracted to be non-dimensional, functioning only at a single point in time and space. While the idea of the economy existing throughout time and space was conceptualized by previous economists, it was not until the 1940's and after when the idea was formalized. Particularly, Enke (1951) and Samuelson (1952) were able to define the spatial allocation problem and formulate it as a programming problem, respectively. This spatial context was refined throughout the 1950's but remained static in time. After Samuelson (1957) noted the similarities in the space and time dimensions, a body of spatio-temporal work developed in the 1960's (summarized by Takayama and Judge, 1972). The ideas described above are at the heart of most current economic theories and, as such, receive attention in this dissertation.

Recognizing the extensive historical and modern role of forests in Maine, it is valuable to produce a market model of Maine's forest-based economy to understand its continuing importance to the state. Even with established methods discussed above, market models for this region are less common than the South or Pacific Northwest due to the nature of Maine's forest and related products. My model fills this need to understand how policies affect the unique industrial forest landscape of Maine.

CHAPTER 2

LITERATURE REVIEW

2.1. Yield, Growth, and Timber Supply Models

There are three primary methods employed when forecasting timber stocks: transition matrices, yield tables, and growth equations (described below). There is also a fourth class of growth models which incorporate the influence of economic conditions on timber supply. All the methods advance some initial forest stock distribution through time and report the resulting expected distribution of trees in the future based on several parameters. Timber supply models are important tools for decision making and are common in any state with a sizable forest economy (Wagner et al., 2003). While timber supply analysis has spatial and temporal aspects, it does not reflect the interactions between the forest resource extraction industry and other industries in the economy (Adams et al., 2002; Gadzik et al., 1998).

2.1.1 Transition Matrices and FIBER 3.0

Transition matrices (i.e. probability or stochastic matrices), as employed by the FIBER 3.0 model (Solomon et al., 1995), are derived from stand table projections, an early method of projecting forest inventories. As the name suggests, future inventories are projected through time by simply adding the anticipated growth for each entry in the initial inventory table, typically in the form of a diameter increment. The anticipated growth may be anything from an informed guess to statistically derived growth increments (Vanclay, 1994).

Transition matrices represent a formalized method for employing stand table projection. Under this framework, each forest and/or species type's growth is represented with a transition matrix that has cells corresponding to survival and growth probabilities for each size class.

Ingrowth and harvest vectors typically supplement the growth matrices to create a more complete representation of forest advancement. Transition matrix models advance forest inventories from one period to the next by applying the transition probabilities in the growth matrix, describing what proportion of an inventory survives or survives and grows. The models then add ingrowth to and subtract harvests from periodic inventories over the model time horizon.

FIBER 3.0 is a forest growth model for the Northeastern United States developed from 4,000 permanent plots between New York and New Brunswick. The model projects growth and mortality for trees across six representative New England (USA) and Maritime (CAN) forest habitats using transition matrices. For each species within each habitat, the model computes the probability of a tree in that class advancing to the next period based on the current class, stand density, amount of hardwoods, and elevation. This first stage of the model is accomplished through a linear regression on the data from the 4,000 experimental plots. Ingrowth for each species in each habitat is estimated in a similar manner. The second stage of the model applies the estimated probabilities to a new, user supplied stand inventory. FIBER 3.0 grows the inventory in five-year increments based on the habitat, species, stocking, management, and others supplied as inputs. The model is maintained within realistic bounds using stand density, tree size, and tree mortality controls. As stand density and tree size both increase beyond certain levels, mortality also increases to maintain stands within observed bounds. However, mortality is also capped to prevent the stand structure from shifting too fast in scenarios not captured by the permanent plots (Solomon et al., 1995).

2.1.2 Yield Tables, Growth Equations, and ATLAS

Yield tables are a straight-forward approach to estimating forest stocks and are one of the oldest formalizations of the process. Yield tables may be relatively simple, describing some forest metric only in terms of stand age and site quality, to very complex, reflecting small subsets of trees influenced by many variables. Basic yields tables, or "normal" yield tables, describe yields from fully stocked, even-aged stands growing regularly. This type of model has obvious drawbacks when it comes to extrapolation as few stands meet these assumptions. One way to address this is through growth and yield equations. Equations are a stricter version of tables that impose some formal relationship between the inventories at different periods; this additional assumption provides more power to extrapolate from observed cases. Yield equations behave similarly to yield tables, predicting total forest yield for some site at some age. Growth equations are a bit more flexible and predict the growth from each period to the next, though both use many similar inputs. In both cases, equations typically measure full stand metrics such as volume or basal area and, as such, do not require inventories with specific tree data to estimate (Vanclay, 1994).

The Aggregated Timberland Assessment System (ATLAS) employs growth equations derived from yield tables (many coming from the FIBER model; Wagner et al., 2003). The ATLAS system is composed of four parts: three parts read and manage data inputs while the final piece, the actual ATLAS model, contains the growth projection mechanics (Mills and Kincaid, 1992). ATLAS models the periodic change in volume per unit area based on stocking adjustment. The relative stocking of an input stand, S_t, is calculated as the ratio of the stand's current volume, V_t, to the stand's baseline maximum volume, Y_t, as in Equation (1); this is how ATLAS defines stocking.

$$S_t = \frac{V_t}{Y_t} \tag{1}$$

These baseline yield tables represent the full potential of each forest condition (Adams and Haynes, 2007). ATLAS then employs stocking adjustment equations to advance relative stocking density. The three equation options in ATLAS follow linear (McArdle et al., 1961), quadratic (Gevorkiantz and Duerr, 1938), and constant forms, respectively, as follows:

$$S_{t+1} = \beta_1 + \beta_2 S_t \tag{2}$$

$$S_{t+1} = S_t + \beta_1 S_t - \beta_2 {S_t}^2 \tag{3}$$

$$S_{t+1} = S_t \tag{4}$$

These periodic relative density ratios are multiplied with the baseline yield table to project the actual inventory of the stand. This imposes a default assumption that stands asymptotically approach some equilibrium structure or will "approach-to-normal." ATLAS also makes similar independent calculations for volume changes due to forest land area gained, forest area lost, harvest, and regeneration to account for the sequential nature of the model's execution. These are aggregated with standard stock-based volume growth to project the total volume change in a period (Mills and Kincaid, 1995). In this light, ATLAS is primarily an accounting system for monitoring shifts in land use, forest types, stocks, and management and was employed by Gadzik et al. (1998) in this context to project the timber supply in Maine.

2.1.3. Tree Lists, Incremental Growth Equations, and FVS

Tree list models are some of the most versatile and complex growth models available. In an inventory sense, they are a compromise between a single-tree approach and a size-class approach. Single-tree approaches record and model many attributes of each tree in an inventory individually while size-class models record only the estimated number of individuals in each size class. Tree list inventories collect many details on individual trees, but not each tree, while simultaneously estimating the number of similarly sized trees in a unit of area, called an expansion factor. Thus, tree-list models can be used for detailed tree information but also for aggregate stand information. In deterministic models, growth is handled by incrementing diameters (or occasionally height) and mortality is incorporated by reducing the expansion factor proportionally to the probability of mortality. These functions, and others, can also be treated stochastically, but typically only a single stochastic aspect is needed to induce sufficient randomness. Record tripling is a mathematical way of splitting each observation to reflect the variation that can be achieved across many stochastic runs without having to aggregate numerous models (Vanclay, 1994).

Common examples of models using incremented growth are those at the foundation of Forest Vegetation Simulator (FVS). The large tree diameter increment model is the most central driver in the FVS model (the model actually estimates the squared diameter increment). In established trees, every aspect of tree development can be linked back to diameter; in estimating diameter increment first, the FVS model can use it as an input to calculate other incremental growth. Though the FVS model variants are formulated differently, most estimate the squared diameter increment in log form using a combination of site factors, like habitat, aspect, and slope, and competition factors, such as crown competition, crown ration, and basal area in larger trees. For smaller trees, FVS employs a similar methodology for height increment instead. In young trees, height is easier to measure and is a better indicator of an individual's future success. Employing separate models for small and large trees introduces the potential for discontinuity between the two at the transition size. Instead of having a single threshold diameter, the FVS model solves the discontinuity problem by designating two thresholds and trees in this intermediate size are predicted with a weighted mean of the two models. While FVS model has many facets and many other features, the growth aspect of the model is largely driven by these two increment models.

2.1.4. Woodstock, SRTS, and Economic Extensions

The Woodstock model, produced by Remsoft, Inc., and the Sub-Regional Timber Supply (SRTS) model operate under a slightly different paradigm than the yield and growth models presented above. While they may be used for forest inventory forecasting, these models emphasize the economic drivers of harvests and management. While these models could be included below as partial equilibrium models, they were included in this section due to their emphasis on the timber resource supply in the face of economic considerations as opposed to an emphasis on the economic equilibrium in the face of natural resource constraints. Both are market simulation models focused on flexibility in their ability to model scenarios. Neither Woodstock nor SRTS have embedded growth models but can accept or overlay user supplied growth models, giving the user a high degree of freedom. For example, both models commonly use ATLAS to power their growth components (Abt et al., 2000; Sendak et al., 2003; Wagner et al., 2003).

Woodstock was designed as a syntax interpreter to allow modelers freedom in choosing the model structure and analytical technique. While different structures and techniques are suited for different tasks, Woodstock attempts to exploit consistent features found in many models. The model accomplishes this by providing very limited built in functionality, instead allowing the analyst to define both the actions and outputs they want to model. This flexibility is extended by Woodstock operating as both a simulation model and an optimization program. In simulation mode, the user can run a specified set of events, or actions, to impact the forest inventory. These may be completely predetermined, optimally chosen, or probabilistically generated. Using a binary search method, Woodstock allows the modeler to pick a single output, such as area or volume, to be optimally chosen by the model. Using Monte Carlo simulation, Woodstock allows the user to explore the range of outcomes from variations to the management actions. In optimization mode, user inputs include an objective function and constraints instead of a list of events. These inputs are converted into a programming matrix which Woodstock uses to generate the optimal management events. Wagner et al. (2003) used Woodstock's simulation option to recreate an ATLAS timber assessment done previously for the State of Maine (Gadzik et al., 1998). The authors extended the assessment by exploring the effect of a selection of planting, herbicide, and thinning scenarios on the present value and sustainable harvest of Maine's timberland, but without considering dynamic market interactions. Woodstock was also used more recently with FIBER and FVS growth models to assess Maine's hardwood stock (Edson et al., 2012).

SRTS's market module was developed with a similar goal in mind: to provide an economic framework that would set over existing forestry models (Abt et al., 2000). Price changes, harvest shifts, and inventory shifts are all modeled consistently with larger scale models. Typically, a market model would report equilibrium prices and quantities given some exogenous shock. SRTS instead uses changing harvest levels (quantity) to solve for harvest shifts (exogenous shocks), as well as the associated price and implied demand (Abt et al., 2000). While a standard timber analysis would focus on how harvests might affect inventories, SRTS places equal emphasis on the price consequences of harvest choices. Within SRTS's market module, demand for various products is determined by stumpage price and exogenous demand shifts under a constant demand price elasticity. Demand projections are aggregated across the entire region being modeled and are specified by the user. Supply is specified at the sub regional and ownership level and is a function of available inventory, price, and external supply shifts, again under a constant elasticity formulation (Abt et al., 2009; Sendak et al., 2003). The model solves the market equilibrium for each product-region-owner combination. Abt et al. (2000) and Sendak et al. (2003) each used an ATLAS-SRTS linked model to compare possible economic scenarios for the southeastern and northeastern forests, respectively.

2.2. Spatial Partial Equilibrium Models

Most forest sector models, economic models which specifically incorporate forest product sectors, have their theoretical foundations in Samuelson's (1952) spatial partial equilibrium formulation. The optimization of Samuelson's endogenous price and quantity model, maximizing producer and consumer surplus less transportation costs, can be handled either one period at a time or throughout all periods simultaneously. The former case is called a recursive dynamic model, which assume that model agents have limited foresight. Their decisions are only based on the current or previous periods. In the alternate formulation, intertemporal models, agents are assumed to have perfect information and can anticipate shocks that may come in later periods. Despite having similar theoretical structures, forest sector models also vary in how they represent consumers, firms, energy use, and forest resource supply. There are also variations in the geographic and temporal scopes of forest sector models. Most intertemporal models have a long simulation horizon and a more detailed account of forest inventory than recursive dynamic models. Due to these factors, forest growth in intertemporal models can often be determined and influenced endogenously through silvicultural treatments, whereas growth in recursive dynamic models is often given as an exogenous growth rate (Sjolie et al., 2010; Latta et al., 2013). Despite differences, forest sector models all include some form of initial or standing timber inventory, an economic characterization of timber processing industries, final product demand, and trade as defining attributes (Kallio et al., 1987).

The Global Forest Products Model (GFPM) is a dynamic recursive forest sector model designed to simulate and predict how forest sectors in different countries behave and interact. The model is designed to account for changes in consumption, imports and exports, and prices due to shocks and policies. The scope of the GFPM is extensive, covering 180 countries and 14 major end products. These include industrial roundwood, fuelwood, sawnwood, wood panels, paper and paperboard, and intermediate wood fiber products such as wood pulp and recycled paper. The GFPM estimates the production of each good by simulating the conversion of wood and other raw materials into intermediate goods and end products for each country. These nested conversions and the associated supplies and demands are represented by input-output flows and manufacturing cost parameters. Shifts in final product demand are determined endogenously by GDP growth, while timber supply is shifted exogenously by growth rates and user selected scenarios (Ince et al., 2011). The model then solves the spatial market equilibrium for each country using price endogenous linear programming (via the Price Endogenous Linear Programming System, PELPS).

As described above for the Samuelson model, the objective function in the GFPM spatial equilibrium is the net social payoff (i.e. the value of the end products to consumers minus the total cost of producing and transporting them, or the total surplus). The GFPM is solved in two phases: static and dynamic. In the static phase, it solves the quantity and price equilibrium that equate demand and supply for all commodities in all regions each year. In the dynamic phase, model parameters are updated to reflect exogenous and endogenous changes from one period to the next. This results in a new demand-supply system for which the model can compute the new quantity-price equilibrium for the next period as dictated by the updates changes. This is iterated for each period in the model projection. Generally, welfare analysis is used to estimate the change in consumer and producer surplus induced by a shock, often a new policy. Because these models only use localized pieces of the demand and supply curves close to the equilibrium point, the GFPM and other partial equilibrium models are not well suited for computing the total welfare for a given scenario. Instead, these models can produce estimates of the change in welfare between scenarios resulting from the differences in production, consumption, imports, exports, and prices due to policy changes (Buongiorno et al., 2003). Thus, partial equilibrium models can effectively assess policies by looking at the changes they cause in specific areas.

In the United States, there is a mandate in the Resources Planning Act of 1974 (RPA) for a nationwide assessment of timber supply, demand, and inventory condition. The mandate is currently met using the U.S. Forest Assessment System (USFAS). The USFAS is composed of three interacting domains: forest use, ecosystem services, and forest dynamics. The engine of the forest use domain is a forest products market model. The GFPM is a powerful model, but because it represents each country (including the United States) as just a single region, it lacks enough detail to satisfy the RPA by itself. So, using the strengths of the GFPM, Ince et al. expanded on the model, defined several U.S. sub-regions to satisfy the RPA mandate, and created the U.S. Forest Products Module (USFPM) to provide forecasts of U.S. regional, U.S. national, and global wood product and timber markets. The USFPM interacts and influences the other two domains through its market projections. Since the USFPM is totally contained within the GFPM, running the USFPM model entails running a complete global trade analysis with GFPM. For this, the USFPM maintains the original structure and data from the GFPM for all the other countries and regions (Ince et al., 2011).

2.3. General Equilibrium Models

The theoretical foundations of many general equilibrium (GE) models are derived from a Walrasian general equilibrium structure. General equilibrium means that all trade flows for all sectors are both accounted for and in balance. In Arrow-Debreu style models, economies share common structural components: households in the economy own factors of production and have a set of preferences for goods described by a utility function; firms maximize profits and generally have constant-returns-to scale production functions; market demands are the sum of household, government, firm, and external demand and are responsive to on prices; finally, equilibrium is characterized by prices and quantity levels such that demand equals supply for all good and income equals expenditures for firms and households. Households own factors of production which they sell to firms, generating income. Firms produce output by combining productive factors with intermediate inputs of goods from other industries. Output of each industry is purchased by other industries, households, or governments using the income received from the sale of factors or taxes (Arrow and Debreu, 1954; Arrow and Hahn, 1971).

2.3.1. Input-output Models

One of the earliest and most common static general equilibrium models is known as input-output modeling, developed by Wassily Leontief in the 1930's. This method tracks the purchases, or expenditures, by each sector or other entity within an economy. The current model used to capture the state of Maine's forest economy is Impact Analysis for Planning, or IMPLAN (Anderson III and Crandall, 2016). IMPLAN provides a detailed view of current inter-industry interactions. It is a complete Input-Output modeling tool that details the interactions between hundreds of industries and can model the impacts of many exogenous system shocks (Olson, 2015). However, it does not capture the spatial relationships within the industry and lacks any predictive ability. Maine's most recent publication in this vein, Maine's Forest Economy 2016, provides a detailed look at the forest economy as it stood at the time. Studies such as this are produced regularly in states like Oregon, Mississippi, North Carolina, and Ohio, among others, with a notable forest products economy (Maine Forest Product Council, 2016; Brandeis and Hodges, 2015; Coronado et al., 2015; Cox and Munn, 2001; Dahal and Henderson, 2013a,b; Henderson and Munn, 2013; Hughes, 2015; Joshi et al., 2013; Latta and Adams, 2000). They provide a good overview of the industries' current growth and impacts and have important applications in policy decisions (Henderson and Munn, 2013).

At the heart of input-output modeling is the social accounts matrix, or SAM. The SAM is a square data matrix that has row *i*, and column *j*, labels for each of the industries in a region (e.g.

manufacturing, commercial logging), the factors of production they use (e.g. labor, capital property), and the social institutions in the region (e.g. households, governments). Table 1 provides an abridged example of a SAM like the one used in this research. A SAM is mostly like a standard data table except that is must obey special rules: it must be square and each row must be equal to its corresponding column.

Industries use factors to produce goods often used along with intermediate inputs, (i.e. goods used in production). In turn, goods are consumed by institutions, which supply the factors of production. The entries of the matrix contain the transfers or payments between the sectors of an economy. Across row *i,* the entries represent demand for good *i* across sectors, or outputs. Down each column *j*, the entries represent the demand of goods by sector *j*, or inputs. In this model of the economy, the primary assumption is that the input and output for each sector are equal. That is, the sum of the i^{th} row and the sum of the j^{th} column are equal if $i = j$. While this is true for the complete SAM, it need not hold for any subset of the sub-matrices described below.

The social accounts matrix is composed of four sub-matrices. These include the direct requirements matrix, which shows the transactions of goods between regional industries (industry x industry); the value added matrix, which accounts for the factors used by each industry (factor and institution x industry); the consumption matrix, which details how institutions consume goods (industry x factor and institution); and the transfer payments matrix, which shows the transfers between factors and institutions (factor and institution x factor and institution). IMPLAN stores these matrices separately, some of which are incomplete, but contains internal algorithms which both complete and connect them. Each of these cells may contain any positive values based on the level of transactions in the region, though many may be zero and they must always yield balanced the rows and columns (i.e. purchases and sales).

	Industries (I)	Commodities (C)	Factors (F)	Institutions (D)	Domestic Trade (E1)	Foreign Trade (E2)
Industries (I)		IC			IE1	IE2
Commodities (C)	CI			CD		
Factors (F)	FI					
Institutions (D)		DC	DF	DD	DE1	DE2
Domestic Trade (E1)	E1I		E1F	E1D		
Foreign Trade (E2)	E2I		E2F	E2D		

Table 1: *An abridged example of basic SAM structures. Letter codes indicate major areas of economic activity.*

Code	**Description**
CI	The local use of commodities by industries as intermediate inputs.
FI	Industrial use of factors to produce final goods.
E1I	Industrial foreign import usage.
E2I	Industrial domestic import usage.
IC	Payments to industries for producing commodities.
DC	Payments to institutions for producing commodities.
DF	Disbursements to local institutions for factor ownership.
E1F	Disbursements to domestic sources for factor ownership.
E2F	Disbursements foreign sources for factor ownership.
CD	Institutional consumption of commodities.
DD	Institutional transfers.
E1D	Institutional domestic import usage.
E2D	Institutional foreign import usage.
IE1	Domestic consumption of industrial exports.
DE1	Domestic consumption of institutional exports.
IE2	Foreign consumption of industrial exports.
DE2	Foreign consumption of institutional exports.

Table 2: SAM transaction codes. Explanations for the transactions represented in respective blocks of cells in the SAM.

2.3.2. Multi-period GE Models

Building on Wassily Leontief's input-output analysis framework, many researchers have developed and improved the general equilibrium framework; however, the basic economic structure of complex dynamic, multiregional GEs is still the input-output table. The first GE model to not use fixed proportion inputs was built in 1960 by Leif Johansen and was called the Multi-Sectoral Growth model, or the MSG model (Jorgensen, 1984). With this model, under a Cobb-Douglas formulation, Johansen introduced a linearized version of a regional economy by representing the percent change in variables instead of the levels. This setup could be solved through matrix inversion and opened the door for more involved GE modelling (Dixon and Rimmer, 2016).

The original MSG model has gone through many revisions and the sixth generation is still currently employed. Considerations added throughout the model's development include special attention to energy use, changes in tax policies, changes in trade tariffs, and attention to environmental impacts; it is often used for policy assessment (Holmoy, 2016). While technically the earliest GE model, different approaches were already being explored in other countries within just a few years. Most notable was the Adelman–Robinson style of computable general equilibrium (CGE) modelling introduced at the World Bank in 1978. Their model emphasized the non-linearity in the economy by altering variable levels directly and had a much shorter effective range for forecasting. The growth and advancement of CGE modelling was largely tied to advances in computing power and an important algorithm produced by Scarf in 1973. It was also highly dependent on the deployment of special use software that facilitated constructing the models for new economists entering the field, namely GAMS and GEMPACK (Dixon and Rimmer, 2016).

Explicit use of CGE models to solely model forestry sectors is very rare simply because CGE models are not well-suited to spatial analyses, an important aspect of most forestry sector models. See Stenberg and Siriwardana for a review of the few CGE models which do focus on FPI sectors (2005). They concluded that there was great promise and merit conceptually, but the application was ultimately underdeveloped so far. Most CGE modeling deals with region-wide topics such as environmental degradation or land use measured across sectors rather than a single, specific sector. If a researcher is interested in a specific sector, they will usually employ a partial equilibrium model. Thus, I can only really discuss CGE model as they relate to regional economies as a whole, not forest related industries alone. Most CGE models used for trade and policy analysis are based on the Global Trade Analysis Project, or GTAP, that was developed in 1992 to facilitate examinations of international economic issues as the global economy becomes more connected.

At the core of the GTAP framework, and the part that is most commonly used in other models, is the extensive database on global trade. These include international trade and transportation data as well as regional input-output tables. A key strength of GTAP is that the database is publicly available and regularly updated, so many researchers can participate and contribute (Hertel, 1997).

In the basic GTAP structure, there are representative regional households that make purchases of private goods, government services, and savings according to an aggregated Cobb-Douglas utility function. This provides a clear measure of social welfare for any given simulation.

This region also interacts in an open economy, trading with the rest of the world by selling exports and purchasing imports. Household income, firms' production, and global trade are all subject to taxes which finance government spending and saving, although this link can be weak in GTAP as government spending may also be stated exogenously. Firms make purchases of factors of production and inputs according a technology tree of nested production functions. Factors of production are combined into a composite good under a Cobb-Douglas or constant elasticity of substitution (CES) structure. This composite good is again combined with key inputs, such as energy, under a Cobb-Douglas/CES formulation. Finally, additional inputs are purchased according to a Leontief structure dictated by the level of nested composite good. This formulation is highly flexible and scales easily with more or fewer sectors (Hertel and Tsigas, 1997). The formulation in GTAP is closely followed by Hosoe et al. (2010).

A more recent model that builds on GTAP is the Applied Dynamic Analysis of the Global Economy (ADAGE) model (Ross, 2008). It is a dynamic CGE model designed to explore how policies will impact aspects of the economy over time. The model is useful for examining many energy, environmental, and trade policies at either the international, U.S. national, or U.S. regional levels. Like GTAP, ADAGE relies on an Arrow-Debreu equilibrium. It also draws its economic data from the GTAP database, as well as from IMPLAN. These economic data include transaction data for firms purchasing material inputs from other businesses and factors of production from households to produce goods, income data for households selling factors and buying goods from firms, and trade flows among regions. As with GTAP, a nested Cobb-Douglas/CES/Leontief formulation is used to characterize firm and household behavior (which maximize profit and welfare, respectively), as well as capital investment (Ross, 2008).

2.4. Limitations in Current Literature

The body of work in circulation covers numerous different modelling methodologies for answering a variety of questions. Despite this, limitations remained to apply existing models to meet my research goal. While a general equilibrium model is perfect for evaluating the ripple effects of policy and shocks, GE models are not well-suited to spatial analyses beyond broad regions. So, the spatial and timber supply aspects must be handled explicitly in a separate partial equilibrium model of Maine's Forest product industry (FPI). More specifically:

- Market models with harvest choice often have discrete, exogenous harvest schedules, even in cases where they may select from multiple schedule options. With this research, given some exogenously specified demand, I want a new model where harvest is determined endogenously based on location, costs, and growth parameters alone. If necessary, the harvest parameter space can be constrained to reflect real life encumbrances. This is an easy way to address the many potential harvest options across all the mills and stands combinations versus numerous harvest schedule variants. Timber supply analyses also come in different resolutions suited to different types of assessments. A medium resolution would allow a meaningful, accurate, and descriptive assessment of the timber supply while also not being overly constraining if used as a prescriptive assessment.
- General equilibrium models rarely contain spatial orientation and when they do it is often limited to different regions, not actual locations. However, given the spatially heterogeneous forest resource and demand centers in Maine, the exact locations where events occur can have important implications on markets, forest management, and

communities. Therefore, I include location information for standing forest stock, wood consuming mills, and final forest product demand centers. As discussed, spatial representation is challenging to implement in the general equilibrium structure. Depicting the select sectors spatially is easily accomplished with a partial equilibrium model.

- Partial equilibrium models are not well suited to examine the impact a single industry has on a region-wide economy. If the FPI was very small compared to the state, the impact may in fact be negligible, but this is not the case for Maine. PE models will tell us how the FPI reacts to policies or shocks, but I am also interested in how those effects influence other parts of the economy. On the other hand, general equilibrium models are particularly well suited to perform policy driven impact analyses, the final objective.

2.5. Research Goal

With a new, spatially explicit general equilibrium model, I wanted to assess how economic and ecological changes in Maine's major export market, forest products, work their way through Maine's economy and affect the lives of Mainers. The model has three unique and important properties: timber supply is completely endogenous to the model, harvesting and forest product activity in the model is represented spatially, and the model is well suited to economic impact analyses for policy and ecological shocks. I combined attributes and elements from timber supply models, partial equilibrium models, and general equilibrium models to achieve each of these goals, respectively. All three pieces of the model are formulated in such a way that the results from one may be directly transferred into the other. This goal is built through four broad objectives:

1. Calculate Maine's current Forest Product Industry and its current economic contributions using a static input-output model,

2. Using data on Maine's current timber supply and growth and mill production and capacities, identify spatially explicit market interactions in the supply chain for forest resources and products,

3. Develop a general equilibrium market model of Maine's Forest Products Industry that can be used to perform economic impact analyses across Maine's economy, and

4. Demonstrate the validity of incorporating spatially allocated resources in a GE model by assessing the impacts of a Spruce budworm outbreak and a forest industry expansion on Maine's economy.

Each of these objectives was designed to address and answer questions about a specific piece of Maine's economy. Modeling each part of the forest products supply chain separately allows the level of detail that is typically required in forest product industry analyses.

CHAPTER 3

STATIC GENERAL EQUILIBRIUM ASSESSMENT OF MAINE'S FPI CONTRIBUTIONS

3.1. Introduction

Given Maine's forestry history, the use of the forest resource has been an integral part of the state's identity and definition for the last 400 years, but forest industry activities tend to occur far from population centers and their current role can be overlooked by many citizens. Periodic economic contribution analyses serve as important benchmarks for the industry's performance and reminders of the industry's importance to the state.

Economic contribution studies provide credible, understandable information that helps the public understand the role of various industries in a region's economy. This information is particularly useful for impressing upon the public the importance of industries that may lie out of sight; it is also used in encouraging legislators and other policy actors to support or consider the studied industries as they set agendas such as tax considerations or worker programs (Henderson et al., 2017). The decline of pulp and paper production in Maine due to a combination of factors, including increased competition from plantation-grown trees in Brazil and other countries, strongly declining demand for printing and writing papers, the high cost of the US dollar, and internet adoption, makes these analyses even more relevant and timely (The Economist, 2016; Johnston, 2016). Given the well-publicized mill closures, global competition, technological advances, and other factors affecting the industry, it has become increasingly important to ensure a broad public understanding of the economic importance of the industry across the state.

Typically based on input-output (I-O) methodologies, like that utilized in the IMPLAN software (IMPLAN, 2018), economic contribution studies have become a popular tool to generate and disseminate economic contribution information about the forest industry in a standardized way. Trade flow data, which details the inter-sector purchases required for production, captures commodity flows between industry sectors, governments, and households within a region. It is used to estimate a sector's external demand and, subsequently, its economic contribution to a region (Henderson et al., 2017). Simply put, for each sector, I-O models explain the inputs needed to produce the industry's output.

There are three types of contribution effects. Direct contributions arise from an industry's employment of workers, wages paid to them, the value of the production (direct sales), and the value added to the inputs in the production process. Indirect contributions result from each industry's purchases of goods and services from supporting industries as a part of doing business, for example, the purchase of a piece of harvesting equipment. As these supporting industries supply needed goods and services, they also generate indirect employment, wages, production, and value in the economy. Induced contributions are those generated by the household purchases of goods and services by employees in both the primary and supporting industries. Induced contributions include things like a restaurant meal that a sawmill worker purchases. The direct effect of production activity in an industry thus has additional effects that are larger and are collectively called multiplier effects. I reported this total effect as the economic contribution of the forest products industry (FPI).

3.2. FPI Contribution Analyses for Maine, 2014 to 2016

In 2016, the Maine Forest Products Council approached researchers at the University of Maine with the goal of updating the previous economic contribution information (also performed by the University of Maine) while attempting to account for the current reality of the industry. The stability of the forest industry in Maine over the long term has meant that the typical time lag between the availability of the data necessary to run an IMPLAN model and the current moment in time has not previously been an issue. Prior to 2016, the most recent analysis of the forest products industry was produced in 2013, using 2011 data; this lag is typical for economic contribution studies using input-output methodologies. However, in the span of two and a half years between November 2013 and May 2016, a series of high-profile closures of pulp and paper mills occurred. In a state where the industry's total contribution was dominated by the value derived from paper making, this cascade of closures introduced a high level of uncertainty as to the overall health of the industry. The market for low-grade material, such as that traditionally consumed by pulp and paper mills or biomass generating plants, improves the economic feasibility of sawtimber cultivation and harvesting by providing additional revenue for forest operations. Forest managers in Maine often depend on the markets for low-grade wood to remove small trees that allow the total biological growth to be concentrated on the higher-quality sawtimber stems. Biomass harvesting also improves the economic returns from entering a stand to harvest any material. Any economic contribution study performed in 2016 that failed to account for the recent mill closures and their impact would be of almost no value when published; no policy agent or citizen would even look at the study results without immediately questioning the current relevance.

The most recent data available, from 2014, would not fulfill the intent of producing credible information about the state of the industry due to the many mill closures. The gap between the desired outcome of the I-O model and the data available highlights one limitation of I-O modeling: it is a static method of evaluation. Regional economic assessments using I-O are a snapshot of the economy as it was when the data were collected; there is no provision for forward-looking estimates or predictions.

3.3. FPI Contributions in 2014

The goal of the initial study was to explore the economic contributions from Maine's forest product industry in 2016 by adjusting estimates for 2014 to reflect structural changes in Maine's economy between then and 2016. For our analysis of the contribution of the forest products industry to the state's economy, I aggregated 20 codes of the North American Industrial Classification System (NAICS) into seven primary sectors (Table 3): Harvesting, Biomass Electricity, Sawmills, Plywood and Veneer, Wood Products, Pulp and Paper, and Wood Furniture. To that list I added one more "primary" sector: the Maine Forest Service (MFS).

While in many states Biomass Electricity production would include multiple feed stocks and not exclusively forest-based sources, Maine has a smaller agricultural sector and, to our knowledge, woody biomass is the only feedstock used for bio-electric on a commercial scale. Data for MFS for employment and compensation were gathered directly from the agency; data for all other sectors were gathered from IMPLAN and the Maine Center for Workforce Research and Information (derived from Bureau of Economic Analysis statistics and the U.S. Census QCEW program).

Sector Title	IMPLAN Code	Subsectors	NAICS Codes
Harvesting	15	Forestry, forest products, and timber tract production	1131
	16	Commercial logging	1133
Biomass Electricity	47	Biomass Electricity	221117
Sawmills	134	Sawmills	321113
	135	Wood preservation	321114
	140	Cut stock, resawing lumber, and planing	321912
Plywood, Veneer, and Engineered	136	Veneer and plywood manufacturing	321211
	137	Engineered wood member and truss manufacturing	321213
	137	Engineered wood member and truss manufacturing	321214
	138	Reconstituted wood product manufacturing	321219
Wood Products	142	Wood container and pallet manufacturing	321920
	143	Manufactured home (mobile home) manufacturing	321991
	144	Prefabricated wood building manufacturing	321992
	145	All other miscellaneous wood product manufacturing	321999
Pulp and Paper	146-148	Pulp, paper, and paperboard mills	3221
	149-153	Converted paper product manufacturing	3222
Wood Furniture	368	Wood kitchen cabinet and countertop manufacturing	337110
	370	Non-upholstered wood household furniture manufacturing	337122
	373	Wood office furniture manufacturing	337211
	374	Custom architectural woodwork and millwork	337212

Table 3. The FPI sectors of Maine. Breakdown of the sectors of interest with associated IMPLAN and NAICS codes, sorted by lowest IMPLAN codes within each sector.

These sectors – our definition of the forest products industry – correspond to aggregations of 25 IMPLAN sectors. After defining our industry of interest, I used baseline data to estimate the economic contributions of the forest products sectors for each year. Following suggested standard input-output methodologies (Henderson et al., 2017; Watson et al., 2015), I estimated the economic contribution from the forest products industry to the state in 2014 (Table 4; Crandall et al., 2017). To ensure the validity of these results, I also analyzed 2014 using

IMPLAN's recommended multi-industry method (Cheney, 2018b). The zero-regional purchases method produces near identical results but attributes all FPI activity to direct effects (Table 5). As the name implies, the method restricts regional purchases of the study sectors to circumvent double counting. While conceptually straightforward and easy to implement, the details of these sector interactions are lost in the simplification. This also limits the method's use for post-hoc impact analyses, like those found in the following section. By preserving the inter-sector purchases, a key benefit of the matrix inversion method is the ability to add new impact events.

2014 (in 2014 $1000 USD)	**Direct Contribution**	**Multiplier Effects**			**Total Impact**
	FPI	FPI	FPI Support	non-FPI	Total
Output	$5,642,301	$676,975	$467,790	$2,987,544	$9,774,610
Employment	14,370	2,181	1,223	21,182	38,956
Compensation	$763,643	$99,597	$57,578	$852,493	$1,773,311
Prop Income	$94,750	$56,327	$36,990	$108,411	$296,478

Table 4. Current nominal 2014 economic contributions of the forest products industry in Maine using matrix inversion. Broken down by impacts, contributions and major sectors. Total and actual row sums may differ due to rounding.

2014 (in 2014 $1000 USD)	**Direct Contribution**	**Multiplier Effects**			**Total Impact**
	FPI	FPI	FPI Support	non-FPI	Total
Output	$6,331,074	$0	$467,644	$2,988,666	$9,787,384
Employment	16,567.2	0	1,221.2	21,108.5	38,896.9
Compensation	$865,248	$0	$57,492	$852,992	$1,775,732
Prop Income	$150,871	$0	$36,940	$108,369	$296,180

Table 5. Current nominal 2014 economic contributions of the forest products industry in Maine using IMPLAN's recommended zero regional purchases method. Broken down by impacts, contributions and major sectors.

	2011 (in 2014 $USD)	*2014 (in 2014 $USD)*
Maine GDP	$55.1B	$55.8B (1.3%)
FPI Value Added	$3.5B	$3.1B (-11.4%)
Percent of GDP	6.38% (1 out of 15.7)	5.56% (1 out of 18.0) (-12.9%)
Total Economic Impact	$8.5B	$9.8B (+15.3%)
All Maine Jobs	794,279	810,672 (+2.1%)
FPI Jobs	38,789	38,956 (+0.4%)
Percent of Employment	4.88% (1 out of 20.5)	4.81% (1 out of 20.8) (-1.5%)
Total Payroll	$1,978.9M	$2,069.8M (+4.6%)
Total State and Local Taxes	$320.1M	$318.5M (-0.5%)

Table 6. Current nominal 2014 economic contributions of the forest products industry in Maine and a summary of 2011 for comparison. Price adjusted to 2014.

3.4. Estimated FPI Contributions in 2016

To update the baseline scenario, I included known mill operation shocks from local news reports on closures and the associated employment reductions (Table 6). Therefore, my 2016 estimates assume no changes in the other six primary sectors in output, employment, and labor income between 2014 and May 2016 (except for reductions in multiplier effect due to the adjusted output from reports). While imperfect, this method avoids the significant delay in waiting for official data to be updated. As with any forecast, the actual 2016 data and contributions differ from my estimate. All prices were adjusted to 2014 or 2016 $USD directly in IMPLAN or using published price indices. The IMPLAN adjustment adjusts each sector individually while the CPI method uses a single conversion factor for everything. For this reason, using the

IMPLAN adjustment is preferred to the CPI adjustment when available since it is based on much more detail information. The 2014 and 2016 results could be directly adjusted in IMPLAN, while the 2011 results were adjusted using published CPI.

Mill	**Location**	**Reported Employment Change**	**Date**
Lincoln Tissue & Paper (downsize)	Lincoln	-210	November 2013
Katahdin Fuel & Fiber	East Millinocket	-200	February 2014
Verso Bucksport	Bucksport	-500	December 2014
Lincoln Tissue & Paper	Lincoln	-180	September 2015
Verso Androscoggin (downsize)	Jay	-300	October 2015
Expera	Old Town	-200	November 2015
Covanta Energy (2)	West Enfield & Jonesboro	-44	March 2016
Catalyst (new machine)	Rumford	+51	March 2016
Madison Paper	Madison	-215	May 2016

Table 7: *The list of notable mill changes occurring in Maine within a 36-month period starting June 2013*

More difficult was trying to estimate the loss of output associated with the closed mills. It was unlikely that the closed mills were equal in productivity and volume to the mills remaining open; in fact, I expected that closed mills were less competitive prior to closure, thereby preventing a simple ratio of employment to output across the industry to be applied to the closed mills. Instead, through iterative conversations with local industry experts, the associated production reductions were derived from the initial lost employment number. In the end, I assumed that closing mills were, on average, 65% as productive as those that stayed open per employee (Peter Triandaffillou, personal communication, May 26, 2016). Thus, the impact of mill closures may be overstated by simply counting the mills that have closed or counting the number of jobs that have been lost. Nonetheless, the closures still represent significant absolute employment and output losses in the industry and a spatial consolidation. These losses also cause ripple effects throughout the forest products industry due to the decline in markets for low-grade wood previously used by those mills. So, using a combination of publicly available information and expert opinion, I generated an employment loss and an estimated loss in final sales for each mill closure which were used to create impact events in IMPLAN.

Using the methods just described, I estimated that Maine's forest products industry had a total 2016 statewide economic contribution, including multiplier effects, of $8.5 billion in sales output, 33,538 supported full- or part-time positions, and $1.8 billion in labor income. The total employment in the forest products industry of 14,562.5 jobs supports an additional 18,975 jobs in Maine (Table 7). The forest products industry supports just over 4 percent of the employment in Maine – around 1 out of 24 jobs in Maine are associated with the forest product industry. This is a reduction from 1 in 20 jobs in 2011. Maine's forest products industry contributes an estimated $2.7 billion in value-added contribution, or just under 5 percent of GSP (gross state product). Just under $1 out of every $20 of Maine's GSP is associated with the forest products industry (Table 8).

2016 (in 2016 $1000 USD)	Direct Contribution	Multiplier Effects			Total Impact
	FPI	FPI	FPI Support	non-FPI	Total
Output	$4,889,267	$617,575	$414,409	$2,620,051	$8,541,302
Employment	12,572.4	1,990.1	1,040.1	17,935.4	33,538.0
Compensation	$664,057	$93,718	$50,977	$748,920	$1,557,671
Prop Income	$93,100	$54,107	$32,933	$95,227	$275,367

Table 8. Estimated nominal 2016 economic contributions of the forest products industry in Maine accounting for mill changes. Broken down by impacts, contributions, and major sectors.

	2011 (in 2016 $USD)	*Estimated 2016 (in 2016 $USD)*
Maine GDP	$55.7B	$55.4B (-0.5%)
FPI Value Added	$3.5B	$2.7B (-21.7%)
Percent of GDP	6.38% (1 out of 15.7)	4.96% (1 out of 20.9) (-22.2%)
Total Economic Impact	$8.6B	$8.5B (-0.3%)
All Maine Jobs	794,279	811,321 (+2.1%)
FPI Jobs	38,789	33,538 (-13.5%)
Percent of Employment	4.88% (1 out of 20.5)	4.13% (1 out of 24.7) (-15.3%)
Total Payroll	$1,999.1M	$1,833.0M (-8.3%)
Total State and Local Taxes	$323.4M	$278.4M (-13.9%)

Table 9. Summary of 2011 economic contributions compared with the 2016 economic contributions, price adjusted to 2016.

	2014 (in 2016 $USD)	*Estimated 2016 (in 2016 $USD)*
Maine GDP	$58.0B	$55.4B (-4.5%)
FPI Value Added	$3.2B	$2.7B (-15.6%)
Percent of GDP	5.56% (1 out of 18.0)	4.96% (1 out of 20.9) (-10.8%)
Total Economic Impact	$10.1B	$8.5B (-15.8%)
All Maine Jobs	810,672	811,321 (0.1%)
FPI Jobs	38,956	33,538 (-13.9%)
Percent of Employment	4.81% (1 out of 20.8)	4.13% (1 out of 24.7) (-14.1%)
Total Payroll	$2,148M	$1,833.0M (-14.7%)
Total State and Local Taxes	$330.9M	$278.4M (-15.9%)

Table 10. Summary of 2014 economic contributions compared with the 2016 economic contributions, price adjusted to 2016.

3.5. Re-analyzing FPI Contributions in 2016

When the data became available for the target year, 2016, I compared the re-estimate of the economic contribution in 2016 (Bailey, 2018) with Anderson III and Crandall's (2016) previous results and to determine if their adjustment technique captures the relevant shocks and produces a meaningful estimate as requested by the industry. Note that Anderson III and Crandall's (2016) results were re-aggregated, but not re-estimated, to match the aggregation used by Bailey (2018) for meaningful comparison. Our estimates produced in 2016 do seem to capture the impact of the modeled shocks effectively. However, it appears that other aspects of the 2016 estimate were only moderately influenced by the modeled shocks. Broadly, Anderson III and Crandall overestimated output and employee compensation and underestimated employment, with direct effects generally being the least accurate. The most accurate predictions were in the intermediate manufacturing sector, which includes pulp and paper manufacturing and thus most of the modeled impacts. Since this was where I most actively modified the 2014 model, the strong performance here is expected. The Intermediate Manufacturing group contribution estimates and the total contribution estimates were within 20% of the reported actual 2016 contributions (Table 11). The other groups exhibited notably worse performance, but aggregate measures were still within 15% of the actual contributions, likely due to pulp and paper's dominance (Table 11; Table 10). Interestingly, the remainder of the impacts, two closing bioelectric plants, are grouped in Harvesting, Logging, and Other Inputs where I saw the worst performance.

There are two influences on these results. The first are missed true, structural changes in the economy either through uncaptured changes in the underlying trade flow data between 2014 and 2016 or uncaptured impacts in the interim. The mill closures discussed here received a lot of media attention, but a small sawmill that closed would face far less scrutiny and be hard to identify through news reports (there were no reports of closing sawmills in Maine in the first 15 pages of a Google search for articles posted during the study period). The second influence is a slight variation in the methods used in both studies. For the 2016 study, the direct contributions were estimated through matrix inversion and in 2018 they were estimated manually through expert knowledge. While both methods produce very similar direct contribution and total contribution results, ceteris paribus, they proportion the intermediate expenditures differently. It is worth noting that this would be an intractable issue if either analysis used the popular zero regional purchase coefficients method (Cheney, 2018b). This explains why the totals of the estimated and actual contributions are similar, but each group of sectors are disparate. This also potentially explains why the Harvesting, Logging, and Other Inputs group is the least accurate since the meaningful difference in the methods is in the intermediate expenditures, represented largely by this input group.

Year Analyzed		
2014	2016	% Change '14 to '16
Actual Using 2014 Data Econ. Contrib.: $10.1B Value Added: $3.2B % of GDP: 5.56% Employment: 38,956 % Employment: 4.81%	**Estimated Using News Reports** Econ. Contrib.: $8.5B Value Added: $2.7B % of GDP: 4.96% Employment: 33,538 % Employment: 4.13%	**Estimated Using News Reports** Econ. Contrib.: -15.8% Value Added: -15.6% % of GDP: -10.8% Employment: -13.9% % Employment: -14.1%
	Actual Using 2016 Data Econ. Contrib.: $7.7B Value Added: $2.3B % of GDP: 3.95% Employment: 35,406 % Employment: 4.00%	**Actual Using 2016 Data** Econ. Contrib.: -23.8% Value Added: -28.1% % of GDP: -29.0% Employment: -9.1% % Employment: -16.8%

Table 11. Two estimates of the economic contributions of Maine's FPI in 2016. (Top) An adjusted estimate of 2014 contributions using news reported changes. (Bottom) An estimate using actual economic data from 2016. Both are compared to the estimate of the 2014 contributions. In 2016 $USD.

Overall, the method of adding impacts works well given its simplicity. An important part of this is the dominance of pulp and paper, but if non-dominant components are shifting instead, the original contribution estimate may still be accurate enough. This method is suitable for short range forecasting. Even with a variation in methods, the aggregate estimates were similar, and avoiding the two-year delay for data could justify the $\pm$15% variation.

2016 $1000 USD	Contribution of Final Manufacturing in the Forest Products Sector, 2016 est.					Contribution of Final Manufacturing in the Forest Products Sector, 2016 act.					Contribution of Final Manufacturing in the Forest Products Sector, % Error			
Impact Type	Direct Effect	Indirect Effect	Induced Effect	Total Effect		Direct Effect	Indirect Effect	Induced Effect	Total Effect		Direct Effect	Indirect Effect	Induced Effect	Total Effect
Output	$121,729	$54,804	$40,268	$216,801		$92,580	$35,665	$32,997	$161,242		31%	54%	22%	34%
Employ ment	755	324	295	1,375		657	225	257	1,139		15%	44%	15%	21%
Labor Income	$32,920	$15,884	$12,550	$61,353		$25,677	$10,812	$10,190	$46,679		28%	47%	23%	31%

Table 12. Comparison of final manufacturing contribution results. Detailed results for 2016 Forest Products' contribution to Maine's economy, estimated and actual and the percent difference between the two. Direct, indirect, and induced effects may not add to total due to rounding.

2016 $1000 USD	Intermediate Manufacturing and Processing, 2016 est.					Intermediate Manufacturing and Processing, 2016 act					Intermediate Manufacturing and Processing, % Error			
Impact Type	Direct Effect	Indirect Effect	Induced Effect	Total Effect		Direct Effect	Indirect Effect	Induced Effect	Total Effect		Direct Effect	Indirect Effect	Induced Effect	Total Effect
Output	$4,459,578	$2,225,432	$943,339	$7,628,349		$4,261,41 9	$1,862,348	$999,597	$7,123,364		5%	19%	-6%	7%
Employ ment	8,250	10,944	6,921	26,115		9,776	12,192	7,774	29,742		-16%	-10%	-11%	-12%
Labor Income	$508,169	$626,549	$294,021	$1,428,739		$537,903	$588,317	$308,696	$1,434,915		-6%	6%	-5%	0%

Table 13. Comparison of intermediate manufacturing contribution results. Detailed results for 2016 Forest Products' contribution to Maine's economy, estimated and actual and the percent difference between the two. Direct, indirect, and induced effects may not add to total due to rounding.

2016 $1000 USD	Harvesting, Logging, and Other Inputs, 2016 est.				Harvesting, Logging, and Other Inputs, 2016 act				Harvesting, Logging, and Other Inputs, % Error			
Impact Type	Direct Effect	Indirect Effect	Induced Effect	Total Effect	Direct Effect	Indirect Effect	Induced Effect	Total Effect	Direct Effect	Indirect Effect	Induced Effect	Total Effect
Output	$302,400	$159,685	$224,118	$686,203	$180,981	$120,405	$115,537	$416,922	67%	33%	94%	65%
Employment	3,574	811	1,646	6,031	2,090	1,536	899	4,525	71%	-47%	83%	33%
Labor Income	$216,067	$55,531	$69,873	$341,472	$69,159	$51,336	$35,679	$156,174	212%	8%	96%	119%

Table 14. Comparison of harvesting, logging, and input contribution results. Detailed results for 2016 Forest Products' contribution to Maine's economy, estimated and actual and the percent difference between the two. Direct, indirect, and induced effects may not add to total due to rounding.

2016 $1000 USD	Total Annual Statewide Economic Contribution, 2016 est.				Total Annual Statewide Economic Contribution, 2016 act				Total Annual Statewide Economic Contribution, % Error			
Impact Type	Direct Effect	Indirect Effect	Induced Effect	Total Effect	Direct Effect	Indirect Effect	Induced Effect	Total Effect	Direct Effect	Indirect Effect	Induced Effect	Total Effect
Output	$4,883,707	$2,439,921	$1,207,725	$8,531,352	$4,534,980	$2,018,418	$1,148,130	$7,701,528	8%	21%	5%	11%
Employment	12,578	12,079	8,862	33,520	12,522	13,953	8,930	35,406	0%	-13%	-1%	-5%
Labor Income	$757,156	$697,964	$376,444	$1,831,564	$632,739	$650,465	$354,565	$1,637,768	20%	7%	6%	12%

Table 15. Comparison of total statewide contribution results. Detailed results for 2016 Forest Products' contribution to Maine's economy, estimated and actual and the percent difference between the two. Direct, indirect, and induced effects may not add to total due to rounding.

3.6. FPI Contributions by Sector and County

Once the contribution of the total industry is broken out by sector, the dominance of the pulp & paper sector becomes clear. However, despite the dominance that certain sectors or certain locations may hold in people's perceptions, neither is more important than the other. The generation of direct economic activity has obvious benefits, but the support counties and supply sectors retain money in Maine that would otherwise leak out of the state through imports of inputs. The FPI plays an important role in every Mainer's life – not just those living in the north Maine woods and not just those working directly in the mills – because of the interconnectedness of the seven forest-based sectors and the involvement of all 16 of Maine's counties.

There are two ways in which a sector may contribute to a regional economy. They may sell products outside the region, bringing sales dollars into the region. Alternatively, they may make a sale to another sector within the region, thereby keeping dollars in the region, as opposed to leaking dollars from the region when sectors import goods and services (Watson et al., 2015). For example, a paper mill makes direct contributions to the state economy by selling paper to many customers out of the state; this brings money into the state that would not otherwise come here. In contrast, harvesting activity in the state that supplies fiber to the pulp mill is keeping that harvesting economic activity in the state, rather than having it come in through imported fiber. Both are essential to capturing the maximum local economic contribution from the resource. Table 16 shows the brought and kept employment effects caused by FPI activity.

In the state of Maine, of the primary FPI sectors, Pulp and Paper will have a large absolute role in both bringing and keeping due to its size (Table 16). However, Table 16 suggests that

Harvesting and Sawmills are responsible for the largest amount of keeping contributions in Maine. This makes sense as all the forest product industries make purchases from harvesting, and sawmilling produces byproducts that may be sold for further manufacture. On the other hand, the Maine Forest Service and Furniture Production keep very few contributions in Maine. This, again, makes sense as the MFS makes no sales to the FPI (or to any other sector, for that matter), while wood furniture is a finished wood product much more suited for export (bringing) than use by another FPI sector (keeping). The forest products industry does not require much wooden furniture as an input for production, so it follows that wood furniture production does not keep very many contributions in Maine. It is, however, a relatively valuable export sector.

Maine FPI Employment Contributions, 2014	**Direct Sector Employment (Bringing and Keeping)**	**Multiplier State Employment due to FPI Sector (Bringing)**	**Multiplier Sector Employment due to FPI in State (Keeping)**
Maine Forest Service	150	62.4	0
Harvesting	3,334	2,123.9	1,273.2
Biomass Electric	127.5	450.8	15
Sawmills	1,644	3,333	527.5
Ply., Ven., & Eng.	695.6	1,074.5	39.9
Wood Prod.	1,742.6	1621	90
Pulp & Paper	5,921.7	15,300.2	233.3
Wood Furn.	755	619.6	1.6
All other Sectors	0	0	22,405
Total	14,370.4	24,585.4	24,585.5

Table 16. The breakdown in employment effects of Maine's forest products sectors. Direct employment is that supported directly by FPI sales to other industries and out of Maine. Multiplier state employment is the amount of additional Maine jobs which are supported by each sector's direct sales. Multiplier sector employment is the number of additional jobs in each sector supported by other forest products sectors pursuing direct sales.

County level employment impact estimates for 2014 and 2016 were calculated based on the share of direct employment in the county in the primary forest products sectors. By breaking down the direct economic activity in the industry by county, it is clear that forestry-related industries are a larger component of economic activity in the more rural, remote northern counties as compared to the more southern and urban counties. However, communities less actively involved in Maine's forest-based sectors are still crucial as they provide many of the support functions necessary for the industry, such as food, financial and insurance services, tools and machinery, and housing.

When considering the county employment that is attributable to the activity of the forest products industry, the direct employment of those in the industry, the readily-visible component including sawmill employees, foresters, and loggers, are easy to identify. However, the employment that is due to the multiplier effects of the industry's activity can be expressed in two ways. The first, called here "multiplier state employment", refers to the state-level employment across all sectors associated with the FPI activities occurring within the county. The second, called "multiplier county employment" refers to the within-county employment across all sectors attributable to the forest industry economic activity in the state.

These two factors can be very different depending on the county (Table 16). For example, in 2016, Aroostook County has the highest direct county-level employment in the industry (1,722). Aroostook County has large areas of working forest land, several sawmills, a paper mill, and biomass electricity production. This FPI business activity occurring in Aroostook County also supports an additional 2,878 jobs across the state, for a total contribution of 4,600 jobs resulting from the forest products industry activity in Aroostook County. In contrast, Cumberland County has lower direct FPI employment (802) and therefore FPI activity within the county supports fewer multiplier jobs across the state (1,328). However, the presence of the FPI across the state results in a large amount of multiplier employment that occurs within Cumberland County: 5,629 jobs. This is due to the preponderance of support industries such as financial services, hospitals, and restaurants that are in Cumberland County.

This recent work shows how important the forest products industry still is, and how different areas and sectors work together to contribute to important economic activity. Adjusting for sector size, pulp and paper manufacturing brings the most value to the forest products economy, while harvesting keeps the most forest product value in state. The analysis demonstrates what is known locally: the forest products industry is an interdependent, interlinked group of sectors, which rely on each other. Focusing on the essential roles of all sectors within the industry is both more realistic and beneficial than focusing on one or two sectors that contribute large “bringing” economic activities in the state.

Urban areas with little active harvesting, few mills, and a more diverse economy than rural regions of the state, such as Portland, Maine in Cumberland County, may perceive that changes in the industry are unlikely to affect their local economy. However, this analysis shows the inter-related nature of all of Maine’s counties in all aspects of the industry. While the rural counties may be more dependent on primary industrial activity related to forests, more urban counties provide many of the support services needed for the industry to prosper. Both the sector analysis and the county analysis point to the need to maintain a complete view of the forest industry, and how it relates to all residents of the state, not just those living near and working in active mills or harvesting.

County	Direct County Employment in FPI (Bringing and Keeping)	Multiplier State Employment due to FPI in County (Bringing)	Multiplier County Employment due to FPI in State (Keeping)
2014			
Androscoggin	1,131.6	2,170.5	1,837.9
Aroostook	1,910.5	3,256.3	1,277.8
Cumberland	905.7	1,532.2	6,639.6
Franklin	1,324.3	2,830.8	566.5
Hancock	531.6	1,123.8	1,102.2
Kennebec	695.2	1,409.1	2,217.1
Knox	306.9	209.1	846.9
Lincoln	73.9	96.2	565.1
Oxford	1,662.1	3,152.0	849.2
Penobscot	1,777.8	2,563.8	2,850.4
Piscataquis	312.1	328.7	277.4
Sagadahoc	78.3	64.2	605.1
Somerset	1,868.2	3,153.5	955.3
Waldo	206.4	246.1	535.3
Washington	861.6	1,538.1	588.7
York	724.2	911.3	2,871.2
2014 Total	**14,370.4**	**24,585.5**	**24,585.5**
2016			
Androscoggin	941.2	1,773.2	1,558.6
Aroostook	1,722.0	2,878.3	1,104.9
Cumberland	802.2	1,328.1	5,628.8
Franklin	1,061.5	2,289.7	486.3
Hancock	417.2	898.3	936.2
Kennebec	559.6	1,141.7	1,881.0
Knox	306.9	209.1	724.3
Lincoln	73.9	96.2	480.4
Oxford	1,446.9	2,727.7	735.4
Penobscot	1,598.4	2,188.3	2,438.7
Piscataquis	311.0	324.5	240.3
Sagadahoc	78.3	64.2	512.7
Somerset	1,633.8	2,691.3	834.7
Waldo	206.4	246.1	455.5
Washington	715.8	1,250.6	508.6
York	697.3	858.3	2,439.4
2016 Total	**12,572.4**	**20,965.7**	**20,965.6**

Table 17. The breakdown of employment contributions of the forest products industry, by county. Direct employment is the number of jobs in each county supported directly by FPI sales from the county to other industries and out of Maine. Multiplier state employment is the amount of additional state-wide jobs which are supported by that county's FPI direct sales. Multiplier county employment is the number of additional county-wide jobs supported by Maine's FPI pursuing direct sales.

CHAPTER 4

A DYNAMIC-RECURSIVE, SPATIALLY ALLOCATED GENERAL EQUILIBRIUM MODEL FOR MAINE'S TIMBER

While many input-output analyses are static, like those just presented, Olson et al. (1984) developed a dynamic I-O model for forest resource management policy assessment. Building from the Forest Service's early version of IMPLAN and relying directly on that input-output framework, they built an interactive model for long-term policy simulation. From period to period, the model has separate modules that handle the changes in social factors such as investment, employment, and population. When compared to a baseline scenario, the results from these modules tells us the socio-economic impacts of different forest resource management policies (Olson et al., 1984). The remainder of this section explains how I built on Olson et al.'s iterative framework to build a general equilibrium model for Maine which explicitly depends on the spatial distribution of forest resources. More recently, Stenberg and Siriwardana (2006, 2008) iteratively combine an ORANI-style CGE model with a simple growth model for forest stocks. My new model follows the concept of these approaches: moving back and forth from socio-economic models (GE) to spatial models (PE) to ecological models (Growth).

4.1. Data requirements to formulate a DR.SAGE model

A DR.SAGE model requires both spatial data and general equilibrium data. There are four key pieces of information that contribute to the novelty of the model. The predominant piece of data is the social accounts matrix (SAM). This table describes how agents interact with one another to produce output. The SAM may be coupled with price and/or quantity data to convert part or all of the SAM to a unit basis instead of a value basis, depending on the research goals. Next, the DR.SAGE needs the production locations for each sector and the capacities associated with that location. Capacities should sum to the relevant total production within the region. This data distributes the production represented in the SAM across space. Third, I incorporated ecological data with the production at each location. This data measures the ecological threshold of each location, indicating its current carrying capacity for production and its ability to recover. For example, a mine is depleted slowly but is non-renewable, a section of stream may be polluted quite quickly but the flow also quickly dilutes and moves it along, or, in my case, stands may be harvested readily but take some time to recover. Finally, if the modeling objectives call for splitting a sector into multiple commodities, the model requires data telling it how the other sectors divide their purchases among those commodities. As an example, in my model the commercial logging sector is split into nine sectors representing the commercial logging of nine classes of trees. The SAM provides the total amount each sector spends on logging, but more information (usually expert knowledge) is required how this value is distributed between the specific commodities.

As with the basis of all GE models, I constructed the SAM from IMPLAN data using the suggestions of Jackson (2002), including a total of 60 sectors. The commodity structure in my SAM has been simplified each industry completely produces exactly one commodity and institution produce none. In reference to Table 1, this results in a collapse of the first two rows and first two columns into one row and column, respectively. This is divided between 35 industries, including 9 forest-based industries and 3 related industries, 3 factors of production, and 22 institutions, found in Table 19. A detailed aggregation description of the specific IMPLAN

PARAMETER	***UNITS***	***SOURCE***
Social Accounts Matrix	$1,000	IMPLAN
Mill/stand capacities	Proportion of Q or $	IMPLAN, FIA Data
Wood Usage Mix/Distribution	%	Survey Data, expert knowledge
Tax rates	%	IMPLAN
Transport Rates	$1000/unit/mile	IMPLAN
Prices	$1000/unit	MFS Reports, US EIA
Quantities	Units	MFS Reports, MFPC correspondence, US EIA
Mill/stand locations	Lon, lat	IMPLAN, FIA Data
Forest Inventories	Mcu.ft.	FIA data

Table 17. Data pieces included in the parameterization of a DR.SAGE model, including units and sources.

sector included in each aggregated SAM sector may be found in Appendix A. The structure of the SAM implicitly imposes some assumption on the economy being modelled. Beyond equal input and output for each industry, additional expenditures are assumed to follow the same proportional distribution as presented in the SAM, which is why SAMs can be, and often are, reduced to a table of expenditures per dollar of output. This imposes a Leontief production structure when SAMs are used for static Input-Output contribution or impact analyses, but this same data can be used to formulate a Cobb-Douglas production function as well. For this model, FPI sectors were converted to a price/quantity basis using data from the Maine Forest Service annual reports while the other sectors were kept to a value basis.

Sector	*Abbreviation*	*Classification*
11 Agriculture, Fishing and Hunting, non-Forestry	11-AGFH	Sector (NONFPI)
Forestry, forest products, and timber tract production	FORE	Forest Related Sector (NONFPI)
Commercial Logging	LOG	Resource Sector (PG)
Support activities for agriculture and forestry	SUPP	Forest Related Sector (NONFPI)
21 Mining, Quarrying, and Oil and Gas Extraction	21-MGOE	Sector (NONFPI)
22 Utilities, non-Biomass	22-UTIL	Sector (NONFPI)
Biomass	BIOM	Forest Based Sector (FPI)
23 Construction	23-CONS	Sector (NONFPI)
31 Non-Forest Product Non-Durable Product Manufacturing	31-NDMF	Sector (NONFPI)
Sawmills	SAW	Forest Based Sector (FPI)
Structural Wood Product Manufacturing	STRUC	Forest Based Sector (FPI)
Architectural Millwork	ARCH	Forest Based Sector (FPI)
Final Product and Miscellaneous Manufacturing	FMWP	Forest Based Sector (FPI)
32 Non-Forest Product Material Manufacturing	32-MMFG	Sector (NONFPI)
Pulp Mills	PULP	Forest Based Sector (FPI)
Paper Manufacturing	PAPE	Forest Based Sector (FPI)
33 Non-Forest Product Durable Product Manufacturing	33-DMFG	Sector (NONFPI)
FPI Related Machinery Manufacturing	MACH	Forest Related Sector (NONFPI)
Wood Furniture Manufacturing	FURN	Forest Based Sector (FPI)
42 Wholesale Trade	42-WHOL	Sector (NONFPI)
44-45 Retail Trade	44-RTAL	Sector (NONFPI)
48-49 Transportation and Warehousing	48-TRWH	Sector (NONFPI)
51 Information	51-INFO	Sector (NONFPI)
52 Finance and Insurance	52-FINA	Sector (NONFPI)
53a Real Estate	53a-REAL	Sector (NONFPI)
53b Rental and Leasing	53b-RENT	Sector (NONFPI)
54 Professional, Scientific, and Technical Services	54-PROF	Sector (NONFPI)
55-56 Management of Companies and Administrative and Support and Waste Management and Remediation Services	55-MGMT	Sector (NONFPI)
61 Educational Services	61-EDUC	Sector (NONFPI)

Table 19. Continued

62 Health Care and Social Assistance	62-HEAL	Sector (NONFPI)
71 Arts, Entertainment, and Recreation	71-RECR	Sector (NONFPI)
72 Accommodation and Food Services	72-TOUR	Sector (NONFPI)
81 Other Services (except Public Administration)	81-OTHR	Sector (NONFPI)
Household Production	HOHO	Sector (NONFPI)
92 Public Administration and non-NAICS	92-ADMN	Sector (NONFPI)
Labor	LABR	Factor of Production (FACT)
Proprietors' Income	PINC	Factor of Production (FACT)
Other Property Type Income	OPTI	Factor of Production (FACT)
State and Local Taxes on Production	SLTAX	Taxes (TAX)
Federal Taxes on Production	FDTAX	Taxes (TAX)
Tariffs on Imports	TAR	Taxes (TAX)
*Households sorted by income groups (9), minimum income indicated by X*1000*	HOHO*X*	Households (HOHO)
Federal Gov't NonDefense	FED	Institution (INST)
Federal Gov't Defense	FEDD	Institution (INST)
Federal Gov't Investment	FEDI	Institution (INST)
State and Local Gov't NonEducation	GOVT	Institution (INST)
State and Local Gov't Education	GOVTE	Institution (INST)
State and Local Gov't Investment	GOVTI	Institution (INST)
Capital	CAP	Institution (INST)
Enterprise	ENTR	Institution (INST)
Inventory/Investment	INV	Institution (INST)
Imports/Exports (External)	EXT	External (EXT)

Table 19. Overview of SAM sectors and their respective economic roles in Maine's economy.

The SAM data play a key role in parameterizing the general equilibrium market module. Since these matrices from IMPLAN are incomplete and SAMs are subject to variability just as any other type of data, I needed to ensure that the SAM built after extracting them meets the core assumption – that input equals output for each sector. I accomplished this using the following algorithm suggested by Hosoe et al. (2010):

$$\min\left(W = \sum_i \sum_j \left(\frac{SAM_{i,j}^{new} - SAM_{i,j}^{old}}{SAM_{i,j}^{old}}\right)\right) \tag{5}$$

$$\sum_j \left(SAM_{i,j}^{new}\right) = \sum_j \left(SAM_{j,i}^{new}\right) \tag{6}$$

$$\sum_{i,j} \left(SAM_{i,j}^{new}\right) = \sum_{i,j} \left(SAM_{i,j}^{old}\right) \tag{7}$$

Eq. 5 minimizes the total percentage deviation from the original SAM. Zero-value entries are held at zero as any increase will cause to W go to infinity and there is no reason to assume new purchases where there were none before. I also ensured that each sector has equal input and output and that the total transfers in the economy remain unchanged (Eqs. 6, 7). An aggregation of the initial SAM used for my model (the SAM changes within the model through resource availability and user supplied impacts) is presented below in color coded direct requirement (Table 20) and sales proportion (Table 21) forms to highlight the general flows in Maine's economy. For example, to produce roundwood the resource sectors, PG, use mostly factors of production, FACT, such as labor. Similarly, those PG sectors receive approximately half of their revenue from the FPI sectors and from exporting. Note that even though the bulk of PG sales are to the FPI and EXT sectors (Table 21, Row 1), the proportional expenditures of FPI and EXT on PG are quite low due to the relative sizes of these sectors (Table 20, Row 1).

These sectors spend money on… (purchase of inputs)

	PG	FPI	NON FPI	FACT	TAX	HOHO	INST	EXT
PG		0.04	0.00	0.00			0.00	0.00
FPI	0.01	0.07	0.00			0.00	0.00	0.09
NON FPI	0.14	0.25	0.25	0.00	0.02	0.58	0.24	0.42
FACT	0.62	0.20	0.48					0.01
TAX	0.01	0.01	0.04					
HOHO				0.69		0.02	0.32	0.02
INST				0.31	0.98	0.16	0.27	0.45
EXT	0.22	0.42	0.22			0.24	0.17	

Table 20. A proportional summary of the initial model SAM's direct requirements. In each column, the Sector at the top spends the corresponding proportion of its total revenue on the industries to the left.

These sectors receive money from… (sale of outputs)

	PG	FPI	NON FPI	FACT	TAX	HOHO	INST	EXT
PG		0.47	0.00	0.08			0.00	0.44
FPI	0.00	0.07	0.06			0.01	0.01	0.85
NON FPI	0.00	0.01	0.25	0.00	0.00	0.34	0.17	0.22
FACT	0.00	0.02	0.96					0.01
TAX	0.00	0.02	0.98					
HOHO				0.58		0.02	0.39	0.02
INST				0.22	0.06	0.13	0.27	0.32
EXT	0.00	0.04	0.44			0.28	0.24	

Table 21. A proportional summary of the initial model SAM's expenditure proportions. In each row, the Sector to the left receives the corresponding proportion of its total revenue from the industries at the top.

Spatial allocation data come from two sources. For all but three sectors, the output is aggregated to the county level and associated with a point near the centroid of the county using IMPLAN data. Locations for external demand centers were determined randomly around the edge of the state with five in New Hampshire representing domestic exports and 15 in the Atlantic and Canada representing foreign exports. Data on the spatial allocation of the disaggregated commercial logging sector is determine using Forest Inventory Analysis (FIA) since it is collected at the plot level and includes information on individual trees within the plots. Maine has over 3,200 plots, each representing approximately 6,000 acres (FIA approximates a regular hexagonal grid layout with ~1.9 mi edges). Using the FIA data, I produced estimates of hard- and softwood timber supply and growth across several product classes (O'Connell et al., 2015). In order to have a broadly defined market which captures the many wood uses in Maine, I defined nine different wood class, based on each tree's potential use and respective species. The three product classes are derived from each tree's DBH and include biomass, pulpwood, and saw logs. These products are each sorted by softwood (SW), hardwood (HW), and noncommercial (NC) wood as found in Table 23. This data also provides the ecological carrying capacity data for the logging sectors. All other sectors are assumed to not have ecological constraints. For each plot in each period, I calculated the current stock of the nine product-by-species combinations in cubic feet and a density dependent growth rate. The distribution of species into these three species groups are in Table 22 below. Some species have limited or no presence in Maine but are included as a safeguard since they are represented in FIA's selection of eastern trees. The distribution of logging sector consumption was assigned using expert knowledge as well as the reported quantities and relative values of the nine classes from MFS annual reports.

FIA Species Group Code (SPGRPCD)	Species Group Name	Model Classification	Prevalence in FIA Data
1	Longleaf and slash pines	SW	0%
2	Loblolly and shortleaf pines	SW	0%
3	Other yellow pines	SW	0.05%
4	Eastern white and red pines	SW	4.49% (92.7% PIST)
5	Jack pine	SW	0.01%
6	Spruce and balsam fir	SW	39.95%
7	Eastern hemlock	SW	4.10%
8	Cypress	SW	0%
Total	**ALL SOFTWOODS**		**48.60%**
9	Other eastern softwoods	NC	8.12%
25	Select white oaks	HW	0.08%
26	Select red oaks	HW	1.48%
27	Other white oaks	HW	0%
28	Other red oaks	HW	0.05%
29	Hickory	HW	0%
30	Yellow birch	HW	4.38%
31	Hard maple	HW	3.95%
32	Soft maple	HW	12.06%
33	Beech	HW	4.69%
34	Sweetgum	HW	0%
35	Tupelo and blackgum	HW	0%
36	Ash	HW	1.92%
37	Cottonwood and aspen	HW	3.94%
38	Basswood	HW	0.07%
39	Yellow-poplar	HW	0%
40	Black walnut	HW	0%
41	Other eastern soft hardwoods	HW	7.42%
42	Other eastern hard hardwoods	HW	0.05%
Total	**ALL HARDWOODS**		**40.09%**
43	Eastern noncommercial hardwoods	NC	3.20%
55	Urban - specific hardwoods	NC	0%
56	Urban - specific softwoods	NC	0%
Total	**ALL NONCOMMERCIAL**		**11.32%**

Table 22: Distribution of FIA species groups to the commercial groups used in my model and their relative prevalence in the FIA data records.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="3">Species Groups, g</td></tr>
<tr><td>Softwood</td><td>Hardwood</td><td>Non-Commercial</td></tr>
<tr><td rowspan="3">Product Classes, p</td><td>Biomass
DBH < 5”</td><td>ComSW.Bio</td><td>ComHW.Bio</td><td>NonCom.Bio</td></tr>
<tr><td>Pulpwood
5” ≤ DBH < 11”
5” ≤ DBH < 9” for SW</td><td>ComSW.Plp</td><td>ComHW.Plp</td><td>NonCom.Plp</td></tr>
<tr><td>Sawlogs
DBH ≥ 11”
DBH ≥ 9” for SW</td><td>ComSW.Saw</td><td>ComHW.Saw</td><td>NonCom.Saw</td></tr>
</table>

Table 23. The nine product-species resource combinations that are included in the model indicated by their abbreviation.

4.2. The DR.SAGE sandwich style model of demand for commodities and services

4.2.1. Putty-Clay Capital Models

The idea of putty-clay capital was first introduced by Leif Johansen in 1959 during his pursuit of a comprehensive economic model. While developing the earliest CGE models, he realized that the classic capital assumptions, either allowing easy substitution or requiring fixed proportions, were unrealistic. Johansen felt a mixture of these assumption better reflected reality (Johansen, 1959). Smooth substitutability, known as putty-putty and often used in partial equilibrium models, allows firms to substitute capital and labor at any time, at any incremental level – the capital-labor decision is malleable like putty. The fixed proportion capital-labor assumption is usually found in general equilibrium models and requires that capital and labor move together as perfect compliments. Johansen, on the other hand, recognized that the firm’s capital choice was incredibly flexible during the investment phase, but became inflexible after the capital is purchased and installed. This inflexibility corresponds to hard clay. So, when firms are choosing to purchase capital, they have *M* machines which they can choose from freely. But, each of these machines is assumed to be operated by a single worker and so has a fixed labor ratio which cannot be changed once installed (Atkeson, 1999). This also implies that the more spent on each machine, the higher each worker's productivity.

Up to Johansen's work, most econometrics was done using the smooth-substitution putty-putty framework. This setup has convenient mathematical properties and the underlying assumptions allow capital to be treated as an aggregate stock, not a collection of different machines. This in direct contradiction to putty-clay's vast array of machines, each with fixed and differing proportional labor requirements. Early economists worried that accommodating this variety in capital choice, instead of a simple aggregate, would create a "curse of dimensionality" and make these models intractable. So, they attempted to refine putty-clay models to avoid the curse and be suitable for dynamic programming. Atkeson and Kehoe (1994) identify conditions which reduce the multitude of capital goods, and their associated labor and energy use ratios, to two state variables and thereby drastically reduce the dimensions of the problem. In turn, these variables can be endogenously solved with dynamic programming.

Given the fixed capital-labor ratio, analyses using putty-clay capital formation tend to focus on issues like capital investment and energy consumption. Empirical evidence suggests that the own-price elasticity of energy is low immediately following a shock in the short run but increases over the long term. This matches the putty-clay framework. Firms are stuck with whatever capital they have in the short run and can only make limited substitutions for energy. Due to this rigid clay capital, short-term energy price increases are more associated with output declines (since machines can be idle) than energy price decreases are with increased output (since machines take time and investment to install). In the long run, they may purchase new or replace capital, allowing for greater flexibility in energy use and long-run energy use is very responsive to changes in the price of energy.

While putty-putty and putty-clay models may suggest similar implications for energy use given a price shock, these similar energy responses do not yield the same final output. Because of the mechanism for new capital, albeit somewhat restricted, putty-clay models allow for adaptation to new prices over time (Lasky, 2003). A firm may change its marginal capital to energy ratio drastically any time it chooses to install a new machine. In contrast, for putty-putty models a permanent shift in energy costs will cause a permanent final output response. This is because in the putty-putty model, capital and energy are always treated as complementary in both the long and short term. Putty-clay models have the two factors as compliments in the short run but allows for substitution of capital for energy (or the opposite) in the long run. Given enough time, firms may install machines with higher or lower capital-to-energy ratios as needed (Atkeson, 1999). Thus, these models have a have a higher long-term cross price elasticity between energy and capital than traditional putty-putty models. Altogether, putty-clay tries to better reflect the investment decisions that firms face and the real time required to change the production process. I adopted a similar logic in the DR.SAGE model: once a production decision is made, it needs to be adhered to in the short term. In short, I used a very simple design in which I expanded the scope of goods that the putty-clay structure applies to and standardize the length of the reinvestment period.

4.2.2. DR.SAGE Adaptation

Imagine a consumer who makes a sandwich every day, each week. At the beginning of each period, the sandwich maker goes to the grocery store and purchases ingredients for the upcoming week. While at the grocery store, the consumer is price sensitive and will buy varying quantities of ingredients based on their delicatessen usefulness and price. However, upon returning home and for the rest of the week, the sandwich maker is constrained to using only the ingredients already purchased: no more, no less. The most economical allocation has the consumer making seven identical sandwiches each using the appropriate proportion of ingredients. This is unaffected by any change in the prices of the ingredients throughout the week. Upon returning to the grocery store for the following week, the sandwich maker reacts to the prices by selecting a different ration of ingredients from the previous week. In this way, the consumer switches between a Codd-Douglas style production function between each period and a Leontief style production function within each period. Formally, if we consider the consumer to have the following constant elasticity of substitution production function, where σ is the elasticity of substitution,

$$Q = b\left(\sum_i a_i F_i^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{8}$$

then in the grocery store the consumer's demand function has some substitutability. As σ approaches 1, the production function becomes a Codd-Douglas style. Again, upon returning home for the week, the sandwich maker loses this substitutability. At home, σ approaches zero and the production function becomes a Leontief style. These derivations may be found in Appendix C.

This is the structure which drives a DR.SAGE model. In each period, model agents make only a single production decision which they are then bound to for the remainder of the period. Each CRM or mill in each sector makes a specific type of “sandwich” that requires a specific mix of “ingredients” (all the agents have access to the same pool of inputs). At the beginning of each period, the SAM describes what mixture of inputs is most appropriate based on necessity and price. The existence of the SAM also presupposes that the input ingredients are in a general market equilibrium even if they have not been shipped and delivered within the model. The spatial allocation algorithm then assigns shipments between CRMs which minimize the cost of transporting the inputs. If an agent can acquire ingredients for less than anticipated, they may reinvest to produce more in the next period and vice versa. Based on the ratio of actual-to-expected costs for each input, the market quantities and prices are readjusted for the next period. If the values are close for an input, that market will remain stable (ceteris paribus). If they are divergent, the market will shift inversely. After the market movements are resolved, the model now has a new SAM describing the new general equilibrium, and the process repeats.

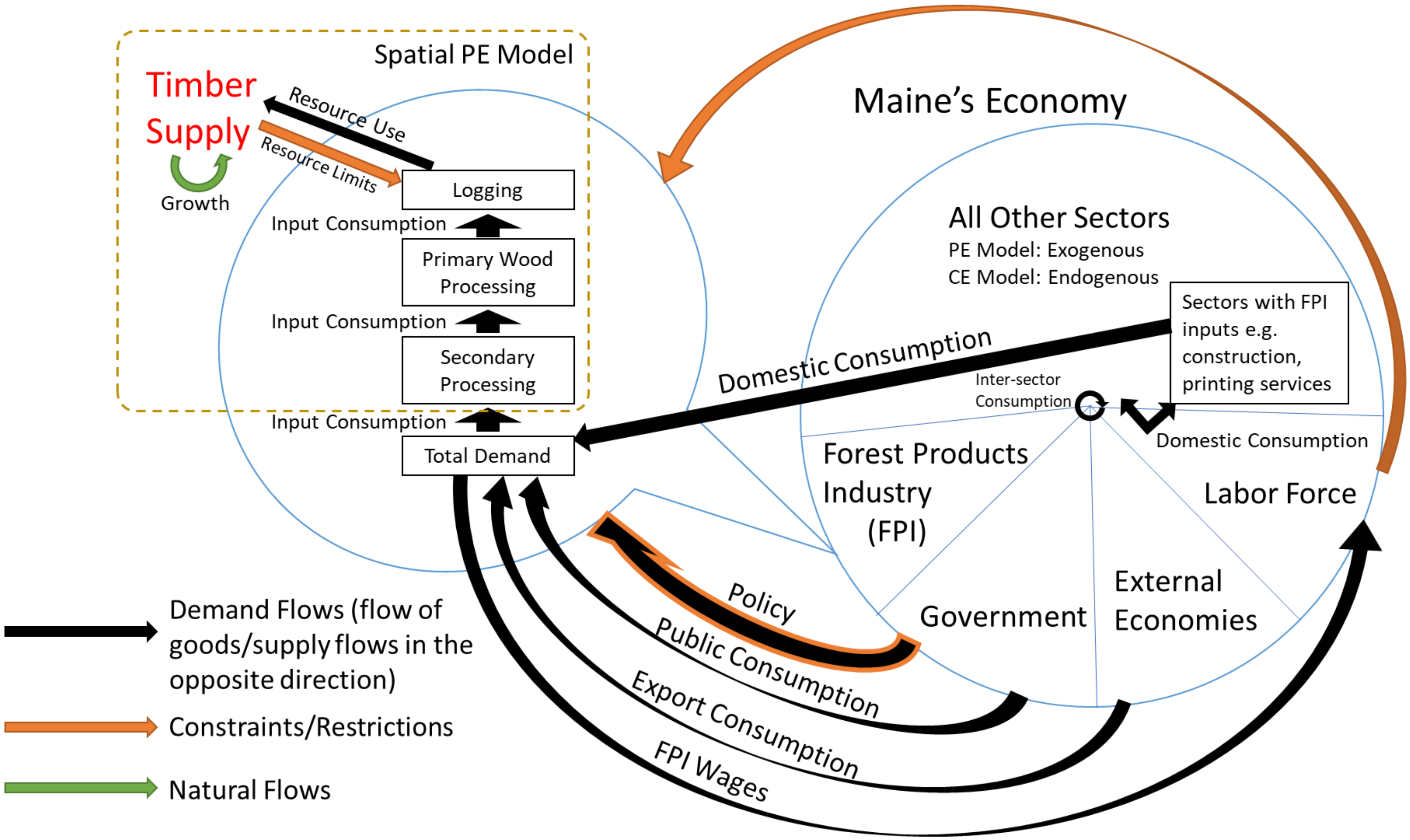

Figure 1: Concept diagram of market interactions represented in the proposed market model for Maine's forest product industry

4.3. Mathematical formulation and recursive structure of DR.SAGE

4.3.1. Resource growth model

Given the nature of Maine's forests, particularly the predominance of partial cuts and prolific natural regeneration, age-based growth models like those found in many Southern US and Pacific Norwest studies are not appropriate to describe forest management in Maine. For Maine, I needed a growth model which is only density, not age, dependent. For example, shade tolerant understory regeneration and overtopped trees in Maine may be quite old but will fail to show any meaningful growth until they are released through disturbance. They then behave like younger trees despite their age. To satisfy the need for an age independent growth formulation, I employed a logistic growth specification for each plot under the following formulation (Eq. 8):

$$stock_{pg,s,t} = \frac{C_s}{1 + e^{-k_s(t-\mu)}} \qquad (9)$$

where $stock_{pg,s,t}$ is the stock of product class pg at time t (years), μ is the inflection point, C_s is the maximum capacity of the stand, and k_s is the maximum intrinsic annual growth rate. Details about the estimation of k_s and C_s can be found in Appendix C. Note that since there is limited age data for Maine forests as described, I could not solve for μ as the maximum growth age or T as the rotation age (which has little meaning in Maine anyway) and t does not represent time since $t = 0$, as is the classic interpretation. However, since μ is simply a shifting constant, it does not appear in the period-to-period discrete growth equation, shown in Eq. 9, which I used to grow the forest stock in my model (discrete in that t may only assume integer values, instead of the truly continuous exponential specification).

$$Stock_{pg,s,t} = stock_{pg,s,t-1}[1 + k_s * \left(1 - \frac{\sum_{pg} stock_{pg,s,t-1}}{C_s}\right)] \tag{10}$$

$$stock_{pg,s,t} = Stock_{pg,s,t} - Xi_{pg,s,t}/(1 - cull) \tag{11}$$

This is the growth specification used by Stenberg and Siriwardana (2006, 2008), following Wilen (1985), and is comparable to the quadratic growth representation used in ATLAS (Adams and Haynes, 2007; Mills and Kincaid, 1992). The logistic specification is also proposed by Chen et al (2017), although they opt to use the similar-propertied Gompertz curve in their analysis. Eq. 10 shows anthropogenic adjustments to the standing stock of resource pg before growth occurs; $Stock_{pg,s,t}$ is the initial stocking in time t, $Xi_{pg,s,t}$ is the harvest in time t, and $stock_{pg,s,t}$ is the carryover stocking to time $t + 1$. I assumed $cull \times 100\%$ of the harvested wood in unusable. In this way, the residual stocking provides the information for the next period's growth. However, it is also employed to adjust the cost of harvesting stands. If I assumed harvesting requires an entry cost (same for all stands) and an additional per unit cost (same for all species and stands), the cost of the harvest is (Eq. 11)

$$harvest\ cost_{s,t+1} = Stand\ Entry\ Cost + Per\ Unit\ Cost \frac{\sum_{pg} Xi_{pg,s,t}}{(1 - cull)} \tag{12}$$

Given the fixed cost, the most economically efficient harvest in terms of total average unit cost is to clear cut the stand, i.e. $\frac{Xi_{pg,s,t}}{(1-cull)} = Stock_{pg,s,t}$. This results in an average harvest cost, AHC, of (Eq. 12):

$$AHC_{s,t} = \frac{Stand\ Entry\ Cost}{\sum_{pg} Stock_{pg,s,t}} + Per\ Unit\ Cost \tag{13}$$

which I saved and used to update the stand's harvest cost for the next period. Thus, if a stand is poorly stocked or heavily harvested previously, it will be relatively more expensive to harvest in the present. This specification allows harvesting intensity to be unrestricted but still have a completely endogenous feedback effect. During the growth stage of the model, the researcher may also implement ecological shocks by manually adjusting the property of each stand. Options here include making stands unavailable for harvest, a harvest cost adjustment for difficult terrain or parcelization, minimum species quota, or maximum allowable cuts.

4.3.2. Making this year's sandwiches: Spatial allocation of commodities

Using the transfer data from the newly balanced SAM, I directly estimated Leontief type production functions. As before, the structure and mechanism of the SAM impose a de facto Leontief production structure on static analyses. Below is a general Leontief production function (Eq. 13):

$$Q_j = min_h({}^{F_{h,j}}\!/_{\beta_{h,j}}) \tag{14}$$

where Q_j is output with $j \in goods$, $F_{h,j}$ is the amount of factor *h* used to produce good *j*, and $\beta_{h,j}$ are the input coefficient of the of *h*^th^ factor when used to produce the *j*^th^ good ($0 \leq \beta_{h,j} \leq 1$, $\sum_h \beta_{h,j} = 1$). Given the computational challenge of handling minimums, the Leontief production function does not explicitly enter my model. By requiring a zero-profit condition, which drastically simplifies the relationship, we can directly solve for the demanded quantities as a fixed proportion of output while avoiding discontinuity. This is reminiscent of assumptions about the SAM and, in fact, each element of the SAM can be viewed as $p_h^D \beta_{h,j} Z_j$, that is an input price times a fixed proportion of the output. For each sector, I estimated the parameters for this specification using the respective SAM entry.

Using data on wood use distribution and mill production capacities, I disaggregated the resource harvesting sector, commercial logging, into the nine specific resource collecting sectors. I also disaggregated biomass electricity, sawmilling, structural manufacturing, architectural milling, furniture manufacturing, pulp and paper production, and miscellaneous wood product manufacturing into 16 pseudo-sectors each, with each pseudo-sector of an FPI sector representing county wide production of that sector for one of Maine’s 16 counties. I termed these county representative mills (CRM). In the example below, Figure 2, logging is disaggregated into hardwood and softwood sectors while the sawmilling Sector is broken into two separate production centers. This economy also has two counties, with one county producing twice as much sawn lumber as the other. So, the first CRM, Mill1, represents the larger county and is twice the size of mill two. Note that different mills or CRM operating in the same Sector will initially require the same fixed ratio of inputs directly in proportion to their size. Here, sawmills use three times more softwood than hardwood and the other sectors use twice as much hardwood as softwood. Upon applying iteration within the model, these relationships will evolve individually depending on the availability of forest resources and applied impacts. Simply, following the example below, if Mill1 has better access to a resource it needs relative to its expectations, it can spend proportionally less on that input and proportionally more somewhere else to expand.

	LOG	SAW	MFG	LABR	TOT
LOG	2	12	3	3	20
SAW	4	3	10	10	27
MFG	10	7	5	6	28
LABR	4	5	10	0	19
TOT	20	27	28	19	94

SAM	Soft	Hard	Mill1(66%)	Mill2(34%)	MFG	LABR	TOT
Soft(75%)	1		6	3	1	1	12
Hard(25%)		1	2	1	2	2	8
SAW	2.5	1.5	2	1	10	10	27
MFG	6	4	4.7	2.3	5	6	28
LABR	2.5	1.5	3.3	1.7	10	0	19
TOT	12	8	18	9	28	19	94

Figure 2. A small example of how an aggregate sector level SAM can be separated into product level and mill level sectors. In this example, the region has two counties. That represented by Mill1 one produces twice as much output as the county represented by Mill2. To produce sawn wood, the CRM sawmills consume softwood and hardwood at a 3:1 ratio.

Given our balanced SAM and price-quantity data, I set the exogenous demand for forest products from exports, institutions and other non-forest related sectors. Given this fixed exogenous demand and anticipated intermediate demand, each of the representative firms in each county searches to satisfy the demand for their final goods as cheaply as possible. I assumed the CRM has already decided on its expenditures on labor, factors, and non-FPI goods, leaving only resources and other FPI goods to optimize costs over. To meet its total demand, the CRM has an anticipated quantity of FPI good it will need to consume as input, $F_{i,m}^{0}$. For each CRM in each period, *m*, purchasing each input products, *i*, their objective is to minimize transportation costs (Eq. 15)

$$\min\left(TC_{i,m} = transport\ cost\right) \tag{15}$$

and the total cost for each FPI good is governed by the amount shipped from each supplier times the supply price, plus suppliers' respective delivery costs which include transportation, average harvest costs, and taxes, respectively, (Eq. 16)

$$TC_{i,m} = \sum_{m'} X_{i,m',m}(P_{S,i} + trate_i dist_{m',m} + diff_{m'} * AHC_{m'})(1 + tax_i) \tag{16}$$

Because $TC_{i,m}$ is clearly a function of mill-to-mill distances, a demand center can optimize its transportation costs by purchasing from the closest mills first, illustrated in Figure 3.

First, using the SAM, prices, and mill capacities, I defined the appropriate output quantities (Eq.16) and input requirements (Eq. 17) for each mill (quantities may also be used directly if the data is available, $\sum_m capacity_{i,m} = 1 \; \forall \; i$).

$$Q_{i,m}^0 = \frac{\sum_j SAM_{j,i}}{P_{D,i}} * capacity_{i,m} = Q_i^0 * capacity_{i,m} \tag{17}$$

$$F_{i,m}^0 = \sum_j \left(\frac{SAM_{i,j}}{P_{D,i}} * capacity_{j,m} \right) = \sum_j \left(F_{i,j}^0 * capacity_{j,m} \right) \tag{18}$$

Then, I created to two pseudo-variables which track the total inputs into and outputs from a CRM (the spatial allocation algorithm only truly optimizes over $X_{i,m',m}$, but it is clearer this way). The amount of i shipped by supply center m' is

$$\sum_m X_{i,m',m} = X_{i,m'} \tag{19}$$

And the amount of i received at demand center m is

$$\sum_{m'} X_{i,m',m} = Y_{i,m} \tag{20}$$

While minimizing the transportation costs, the total amount of input, *i,* received across suppliers, *m',* is a function of the anticipated quantity. This happens in one of two ways: one-to-one demand or aggregate demand. Stands (Eq. 21) and external demand centers (Eqs. 23, 24) demand inputs in aggregate. This is because exports must simply leave the state, not reach an explicit destination, to qualify as an export and must only come from out of state to be an import (see below Eq. 28). Similarly, an unharvested stand does not necessarily have zero capacity to produce timber and a stand with the capacity to produce timber need not be harvested (see below Eq. 26). All the other mills and CRMs (Eqs. 20, 22) demand inputs on a one-to-one basis since they are competitive firms. This results in five separate demand function depending on the input:

$$F^0_{i,mill} \leq Y_{i,mill} \tag{21}$$

$$F^0_{i,stnd} \sum_{pg} X_{pg,stnd} \leq Y_{i,stnd} \sum_{pg} Q^0_{pg,stnd} \tag{22}$$

$$F^0_{i,endog} \leq Y_{i,endog} \tag{23}$$

$$\sum_{i} F^0_{i,dexog} \leq \sum_{i} Y_{i,dexog} \tag{24}$$

$$\sum_{i} F^0_{i,fexog} \leq \sum_{i} Y_{i,fexog} \tag{25}$$

I also ensured that the amount any commodity supplied is less than or equal to its total production. This also results in four different supply balances. Again, most mills and CRMs supply output according to their capacity (Eqs. 25, 27) while stands and exogenous supply centers are not bound by capacity and simply supply their outputs in aggregate (Eqs. 26, 28).

$$Q^0_{fpi,mill} \geq X_{fpi,mill} \tag{26}$$

$$\sum_s Q^0_{pg,stnd} \geq \sum_s X_{pg,stnd} \tag{27}$$

$$Q^0_{aos,endog} \geq X_{aos,endog} \tag{28}$$

$$\sum_{exog} Q^0_{ext,exog} \geq \sum_{exog} X_{ext,exog} \tag{29}$$

Additionally, the amount supplied from a location may not exceed the ecological capacity at that location, accounting for cull (15%) and participation.

$$(1 - cull) * prtcptn_{stnd} * Stock_{pg,stnd} \geq X_{pg,stnd} \tag{30}$$

The exogenous final price is derived using an average transportation distance representing the expected distance at which demander can find the input commodity they require (Eq. 20)

$$P_{D,i} = \left(P_{S,i} + avgdist_i dist_{m',m} + diff_{m'} * AHC_{m'}\right)(1 + tax_i) = \frac{\sum_j SAM_{j,i}}{Q^0_i} \tag{31}$$

or equivalently the total value of each sector divided by its output. Only shipments, $X_{i,m',m}$, and therefore total cost, deliveries, and receipts, are determined endogenously while all other parameters are exogenously supplied from the general equilibrium module and the ecological module. Aggregate expenditures from factor consumption for each forest product sector from this partial equilibrium module are returned to the GE module.

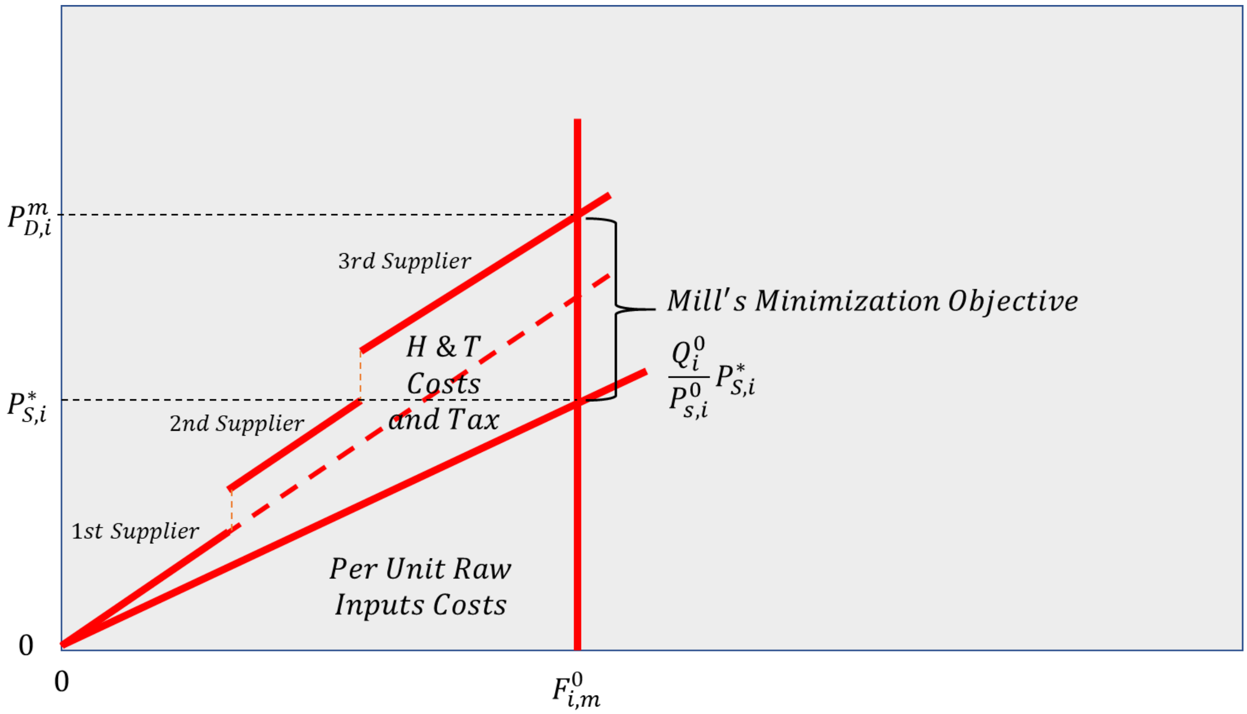

Figure 3. Representative plot of a mill's demand for each good and the supply curve across three progressively more expensive suppliers. In this example, two suppliers reach capacity before meeting the mill's required input is achieved. The dotted line represents the case where the first supplier can meet the demand. H&T stands for harvest and transportation.

4.3.3. Going back to the grocery store: Handling reinvestment for the next period

The total difference in anticipated costs and actual cost across inputs, $\sum_i (P_{D,i}^0 F_{i,m}^0 - TC_{i,m}) = inv_m$, is a key output from the spatial allocation and is used to adjusted each mills expenditures in the SAM for the coming period. Residuals from underspending on resources are invested in profit, income, and non-spatial goods; overspending on timber results in these categories being cut back in the next period. To implement the reinvestment, I reallocated each CRM's inv_m residual within its respective column of SAM, resulting in a net-zero direct effect impact. I then used Leontief style impact analyses to analyze the ripple effect each reinvestment and subsequently adjust the SAM to reflect new expenditures in the next period with the following iterative algorithm. Let $MillA$ be the current direct requirements matrix for the demand centers derived from the SAM and $IO\Delta$ be the adjustment matrix to the mill's input expenditures based on expenses. Then, each element of the adjustment is

$$IO\Delta_{i,j,m} = \left(MillA_{i,j,m} + \frac{TC_{i,m} - P^0_{D,i}F^0_{i,m}}{inv_m} \right) inv_m * \frac{capacity_{j,m}}{\sum_j capacity_{j,m}} \tag{32}$$

Note that by design, this a net-zero adjustment within each output and mill. Next, I created an impact vector by summing over all outputs at all mills and CRMs

$$E_i = \sum_{j,m} IO\Delta_{i,j,m} \tag{33}$$

and then loop through the rounds of spending in the SAM (the impacts values usually become meaninglessly small within eight rounds (Schaffer, 2010), but there is very little computational loss in going to 100 to be certain)

$$\begin{gathered} for\ \ l = 1, \ldots, 100\ (\\ IMP_{j,dom,l} = A_{j,dom} * E_{dom} \\ E_{dom} = \sum_j IMP_{dom,j,l}) \end{gathered} \tag{34}$$

This yields the same aggregate effect as using the multiplier $(I - A)^{-1}$ but instead details the sector-by-sector transaction impacts (Schaffer, 2010). The total impact to the SAM is then

$$SAM\Delta_{i,j} = \sum_m IO\Delta_{i,j,m} + \sum_l IMP_{i,j,l} \tag{35}$$

$$SAM'_{i,j} = SAM_{i,j} + SAM\Delta_{i,j} \tag{36}$$

Finally, returning to a Cobb-Douglas setup, the adjusted SAM data is used to calculate a new output level. Using these adjusted outputs and I recalculated the associated capacities and input requirements.

$$Q_{j,m}^{1} = Q_{j,m}^{0} \prod_{i} \left(\frac{P_{D,i}^{0} F_{i,m}^{0} + IO\Delta_{i,j,m}}{TC_{i,m}} \right)^{MillA_{i,j,m}} \tag{37}$$

$$capacity_{j,m} = \frac{Q_{j,m}^{1}}{\sum_{m} Q_{j,m}^{1}} \tag{38}$$

$$F_{i,j,m}^{1} = \frac{Q_{j,m}^{1} P_{D,j}^{0} MillA_{i,j,m}}{P_{D,i}^{0}} \tag{39}$$

Before preceding to the next round, prices are set to ensure supply and demand balance and $F_{i,j,m}^{1}$ and $Q_{j,m}^{1}$ are adjusted respectively according to Cobb-Douglas production and (approximated) derived demand. I employed a first order approximation for Cobb-Douglas derived demands, as described in Appendix E, for potential future incorporation into the linear spatial allocation module. These balanced supply and demand values are then assigned to the parameters $F_{i,j,m}^{0}$ and $Q_{j,m}^{0}$ for the next round of spatial allocation. With balanced quantities, adjusted prices, adjusted forest stock, and implementation of any relevant policies, the model may be advanced to the next period.

$$P_{D,i}^{1} = \frac{2P_{D,i}^{0}}{\frac{\sum_{m} Q_{i,m}^{1}}{\sum_{j,m} F_{i,j,m}^{1}} + 1} \tag{40}$$

$$Q_{j,m}^{0} = Q_{j,m}^{1} \frac{P_{D,i}^{1}}{P_{D,i}^{0}} \tag{41}$$

$$F_{i,j,m}^{0} = F_{i,j,m}^{1} \left(2 - \frac{P_{D,i}^{1}}{P_{D,i}^{0}} \right) \tag{42}$$

I also used Leontief style impact analysis to implement economic growth and shocks within the model during this phase. External economic growth in DR.SAGE assumes a 0.2% increase in population each year. Economic shocks come in a variety of styles: external demand shifts, internal demand shifts, production function/technical change, and tax policies. The appropriate first order specification of each shock must be exogenously determined by the modeler. Unlike reinvestment, economic shocks need not be net-zero adjustments. Crandall et al. (2017) use this type of exogenous shock modeling to examine the effects of both closing paper mills and opening biofuels plants. These analyses also provide examples of converting news reports or engineering specifications into first order impacts. Like all general equilibrium models, there is an initial business as usually (BAU) run of the model which includes no shocks at all. Future runs which do include shocks are compared to the BAU run to determine the relative effect of the shock happening versus not.

4.4. Baseline Results

The baseline DR.SAGE model describes how Maine's economy could grow over the next ten years. In the base model, there are only two factors which drive expansion: population growth and improvement from spatial optimization. I assumed the population grows 0.2% per year, directly increasing each sector's output by a proportional amount because CGE models are homogenous in degree one. Growth from spatial optimization is determined endogenously for each supply and demand center (SADC) and aggregated for each sector. To estimate this amount, subtract the 0.2% population growth from the annual growth values reported. Given these limited drivers, the results from the base model are somewhat predictable.

4.4.1. Economy-wide Results

Using the baseline DR.SAGE assumptions, I estimated that Maine's GDP will increase by \$3.1B, or 5.3%, over the next ten years (Table 24). GDP increases consistently with an average increase of 0.53 % per year. This is attributable to population growth and spatial optimization, so this represents a real growth in GDP. Similarly, all the other outputs presented are real increases in quantity, not value. Overall value increases are a composite of quantity increases and price increases. The larger change in the first year is common for all sectors and represents the immediate boost from moving from a description of Maine to an optimization.

	Annual Regional GDP	**Annual Increase**	**Increase from 2015**
2015	57,536.9	0.83%	-
2016	58,012.2	0.47%	0.83%
2017	58,285.5	0.40%	1.30%
2018	58,517.6	0.49%	1.70%
2019	58,804.4	0.50%	2.20%
2020	59,096.6	0.48%	2.71%
2021	59,382.5	0.49%	3.21%
2022	59,675.4	0.47%	3.72%
2023	59,955.6	0.53%	4.20%
2024	60,273.5	0.53%	4.76%
2025	60,595.4	-	5.32%

Table 24. Maine's annual regional GDP, in $1M USD, the percent increase between years, and the total increase in GDP from 2015.

The non-FPI sectors exhibit interesting, if predictable, behavior. For the most part, after an initial shift in spatial allocation, each sector remains constant with respect to countywide output and growth. There are some notable exceptions, including transportation and warehousing, retail trade, wholesale trade, and the harvesting sectors (discussed below). Over the ten-year horizon, transportation and warehousing, retail trade, and wholesale trade each make steady progress towards reallocating their production into York, Cumberland, Androscoggin, Kennebec, and Penobscot, representing the I-95 corridor. It makes sense that these infrastructure dependent sectors move where they have easy access. While I-95 is not explicitly in the model, it is loosely represented by the population distribution. The transportation

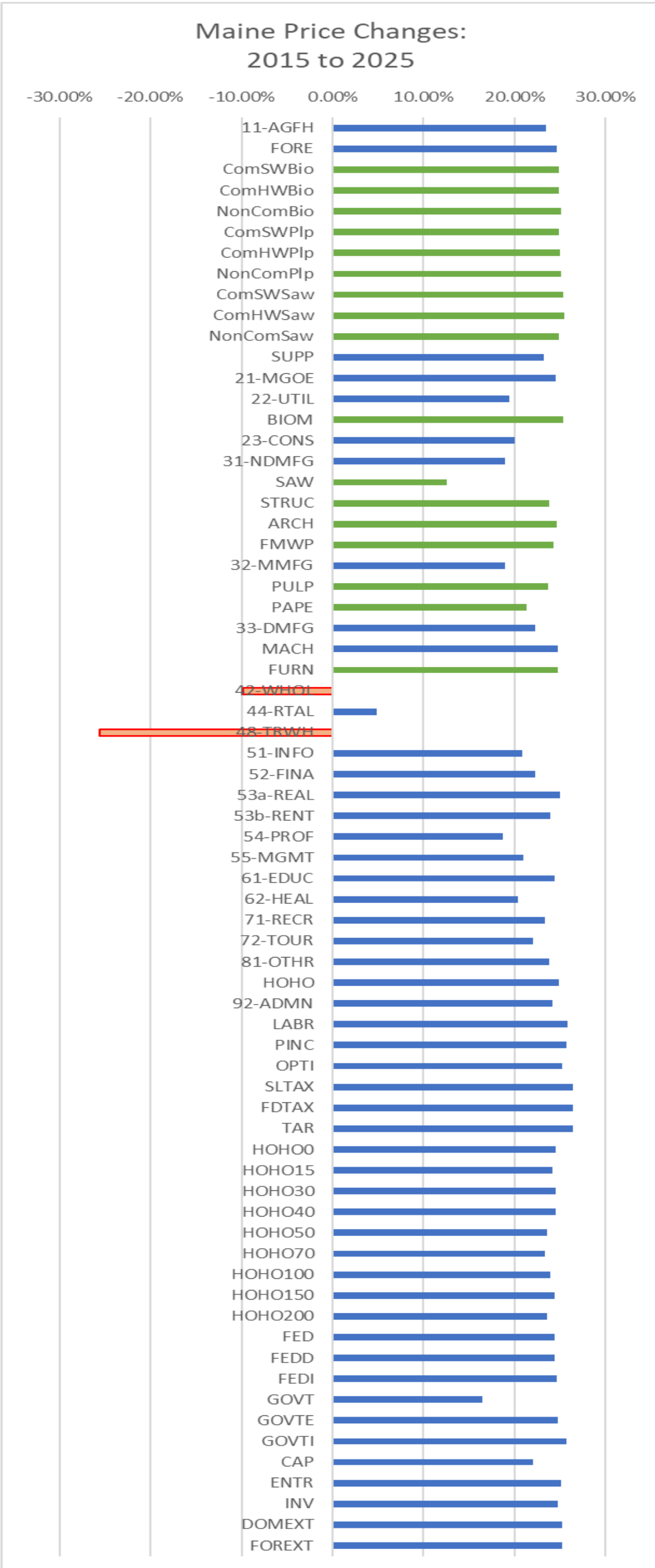

Figure 4. Price changes from 2015 to 2025 generated by the baseline DR.SAGE model

sector is also the only sector which consistently declines in aggregate production and price, but this is also expected: transportation models seek to minimize transportation and thus work against the sector's growth. This is because DR.SAGE models are prescriptive, not descriptive. Annual county output and growth plots for every sector can be found in the Supplemental Materials but are not included here.

The price changes in Maine are exogenously driven by a 2% annual inflation, creating a 21.9% increase over ten years, ceteris paribus. On average, the sectors average a 22.1% increase over the model horizon, though there is clear variance (Figure 4). In the same exception as above, we see a major price decrease for transportation as the objective of the model is to diminish the transportation sector. Retail and wholesale trade also break from the trend of the rest of the sectors, but this is due to their higher level of spatial reallocation versus other sectors. Generally, a smaller price increase than 22% indicates that a sector has relatively better spatial access to its inputs (leading to higher output) than its customers have to theirs (leading to lower quantity demanded). A larger price increase indicates the sector has relatively less spatial access to its inputs.

4.4.2. Harvest Results

The harvest of Maine woods increases by almost 28 million cubic feet, or 4.7%, by 2025 (Table 25). This represents an average 0.46% increase in harvest volume each year. In this same period, the price of each product-species combination increases consistently by around 25.1%.

	Total Annual harvest (MMcu.ft.)	Annual Increase	Increase from 2015
2015	592.3	0.43%	-
2016	594.9	0.48%	0.43%
2017	597.7	0.43%	0.91%
2018	600.3	0.44%	1.35%
2019	602.9	0.46%	1.79%
2020	605.7	0.47%	2.26%
2021	608.5	0.47%	2.74%
2022	611.3	0.46%	3.21%
2023	614.2	0.47%	3.69%
2024	617.1	0.49%	4.18%
2025	620.1	-	4.69%

Table 25. Total annual harvest from Maine forests in MMcu.ft., the annual increase in total harvest, and the overall increase in harvest from the 2015 baseline.

Generally, most of the pulpwood and sawlog harvesting occurs in the northern and western counties (Figures 5-8), with Aroostook being a prominent supplier of all wood. If these stocks are sufficiently depleted (driving harvest costs up), the harvests will generally move first east, then south. This is heavily influenced by the specific locations of the demand centers, of course (e.g. if all the demand centers are south of the current harvest areas, new harvest areas will likely move south exclusively). Biomass harvests begin in the middle of the state in Waldo, Penobscot, and Aroostook, but expand westward over time (not shown).

Due to the highly dynamic nature of stand harvest levels, I did not present the percent change in harvest for each county due to small denominators. When moving from a depleted stand to an unharvested stand, the percent change is huge (if not infinite). Since this big change is due to the small initial harvest, not necessarily a large increase, and since the harvest level will usually fall again in a few years, these percent changes are not as informative as for other sectors.

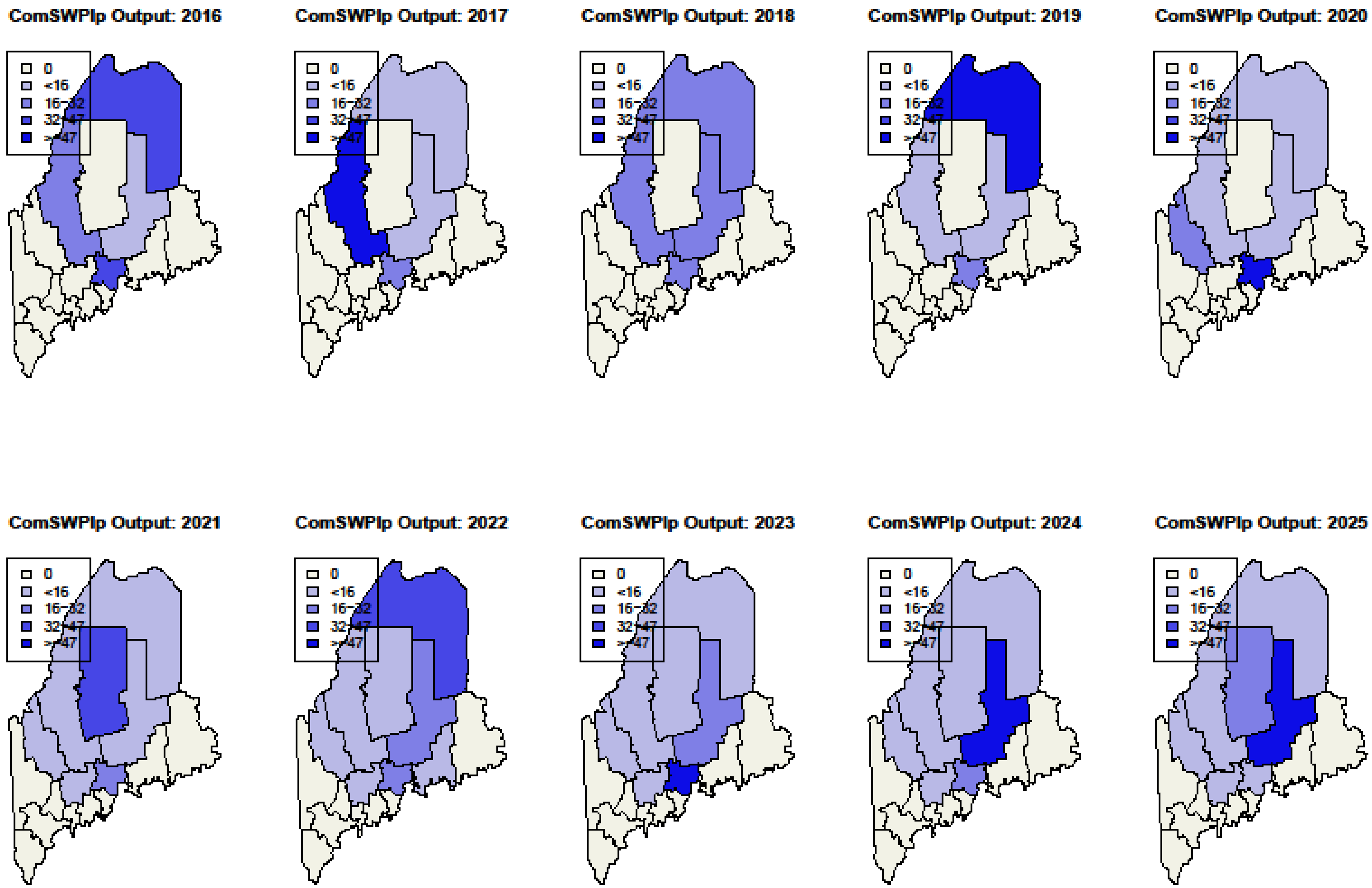

Figure 5. DR.SAGE baseline estimate of the harvest of softwood pulp (ComSWPlp) by county in MMcu.ft..

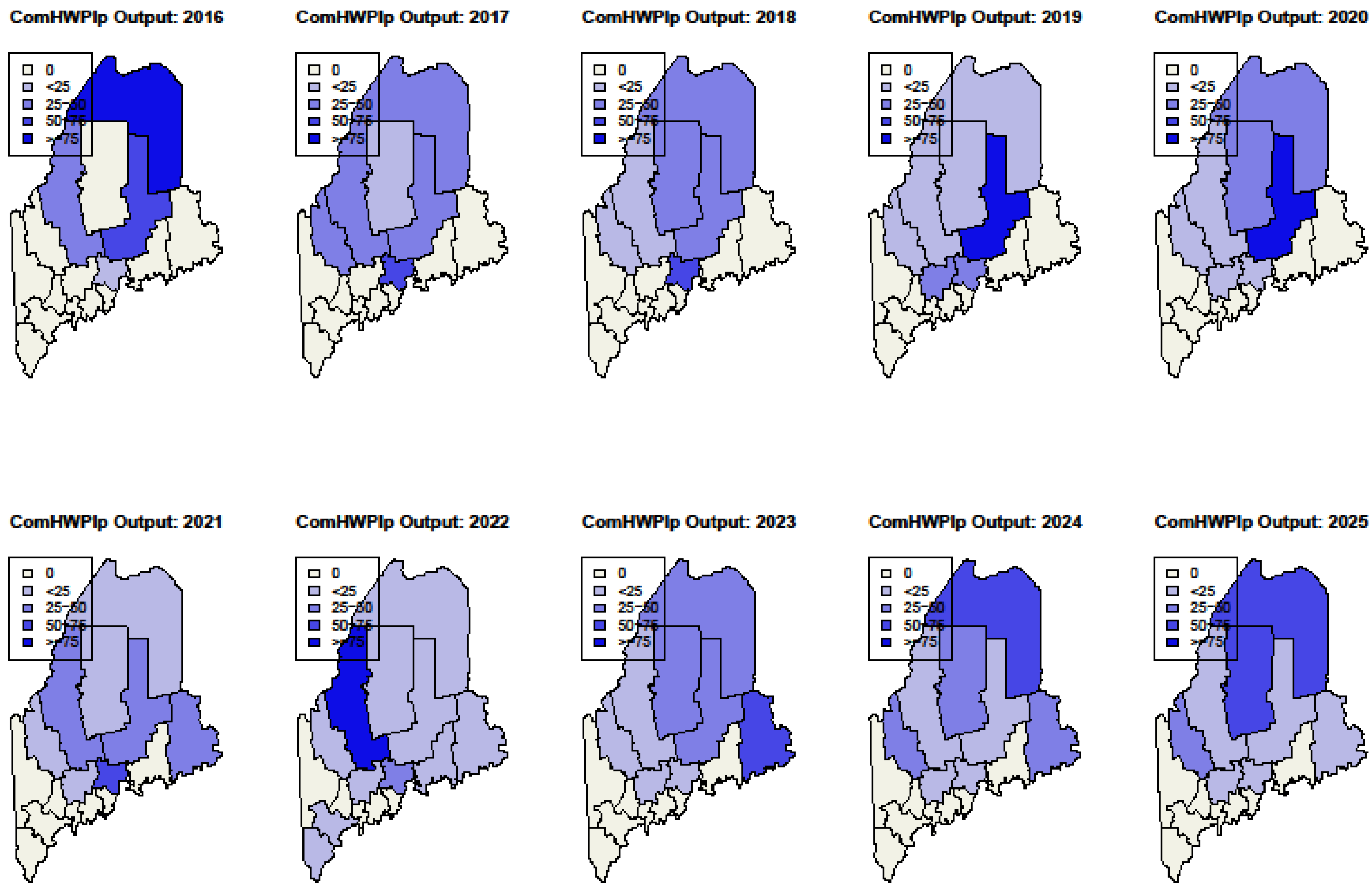

Figure 6. DR.SAGE baseline estimate of the harvest of hardwood pulp (ComHWPlp) by county in MMcu.ft..

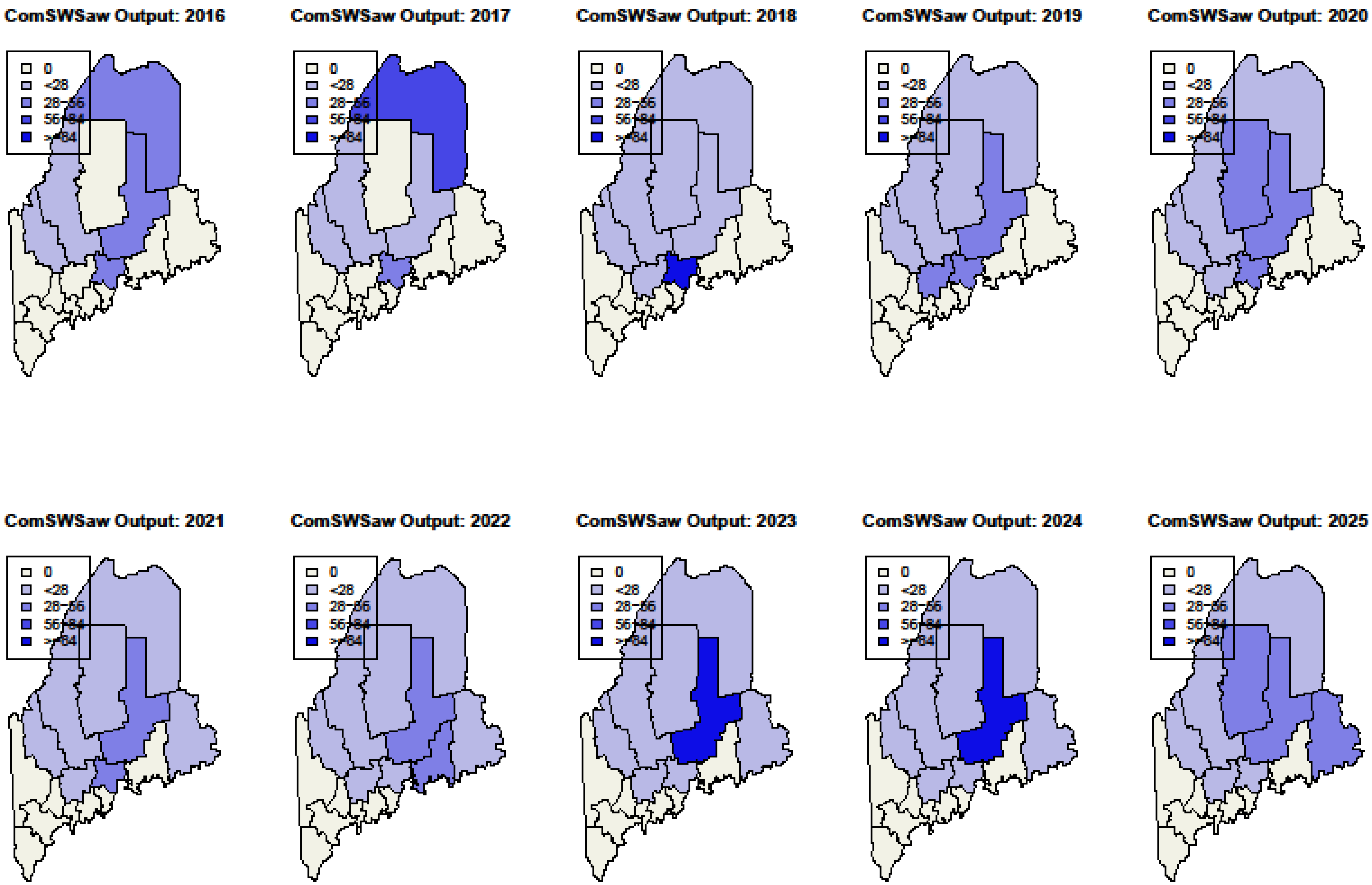

Figure 7. DR.SAGE baseline estimate of the harvest of softwood saw logs (ComSWSaw) by county in MMcu.ft..

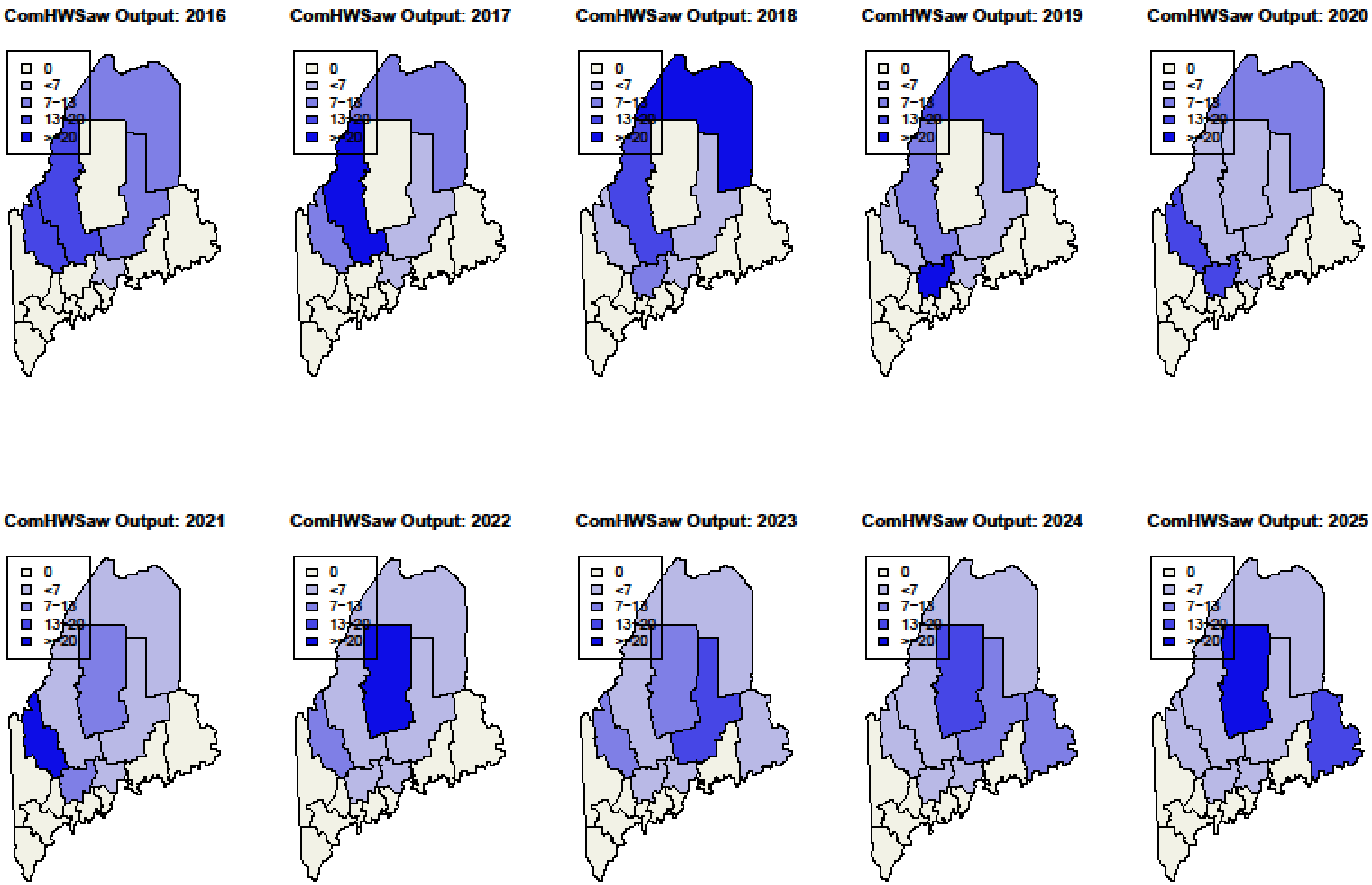

Figure 8. DR.SAGE baseline estimate of the harvest of hardwood saw logs (ComHWSaw) by county in MMcu.ft..

4.4.3. Forest Products Industry Results

Of particular interest in the DR.SAGE model are the forest product sectors. Ironically, this makes these sectors more static than others in the baseline model because they are better defined. Since these sectors are represented in just a few counties and a sector cannot move into a county where it was not before, there are fewer inter-county substitutions available for production. In contrast, there are 100 stands, so these sectors have a lot of spatial substitutability in a major input. Growth is highly consistent between counties for all the FPI sectors and ranges between 0.3%-0.7% per years, except for Sawmills (SAW). Since the outputs of the sectors grow similarly in each county, relative changes in output between the counties are slow to change. Figures 9-14 provide details about how specific FPI sectors might develop in Maine under the DR.SAGE assumptions. Maps of more spatially consistent forest product sectors may be found in Appendix E.

Sawmills exhibit slightly different behavior than the other FPI sectors and this sector is estimated to expand its output by over 16% by 2025. Despite wood being an important input for all FPI sectors, only sawmills and biomass plants spend a large proportion of their outlays on harvested wood. The many stands in this DR.SAGE model make spatial substitution easier. Sawmills additionally spend a large amount on rebuying sawn wood products for further processing, which are assumed to be made in house due to optimization. Thus, these two inputs are easier for sawmills to acquire compared to other FPI sectors' input, allowing for a faster rate of expansion each year. Also, sawn wood is a more integral input to the development of Maine's infrastructure than other FPI goods, which are largely exported. So, sawmills benefit more from expansion in other parts of the economy. For example, sawn wood is a moderate input to construction. Construction, in turned, is purchased as capital and as real estate. Capital is purchased to generate property income and real estate is purchased by households. Both household income and property income grow with any expansion in any sector, so sawmills will benefit as well. A consequence of this expanded production is a slower increase in prices. The price of sawn wood only increases 11.3% by 2025 compared to the benchmark of 22.1% (Figure 4).

There are similar linkages for biomass, but they are not as strong. Biomass mills spend slightly less than sawmills proportionally, but also demand a much less specific and less desirable class of wood. While normally this would be a benefit, as with the plethora of stands being a benefit to wood users, the lack of alternate demanders of biomass deflates the advantage this provides since transportation costs are determined across sectors. The limited number of biomass mills also limits the spatial substitution of biomass electricity output. These mills don’t have the liberty of shifting their production with the accessibility of their wood inputs as the more widely represented sawmills can. Finally, biomass is simply not a large part of electricity generation in Maine, so an increase in electricity consumption by households and sectors is only fractionally translated to the biomass sector.

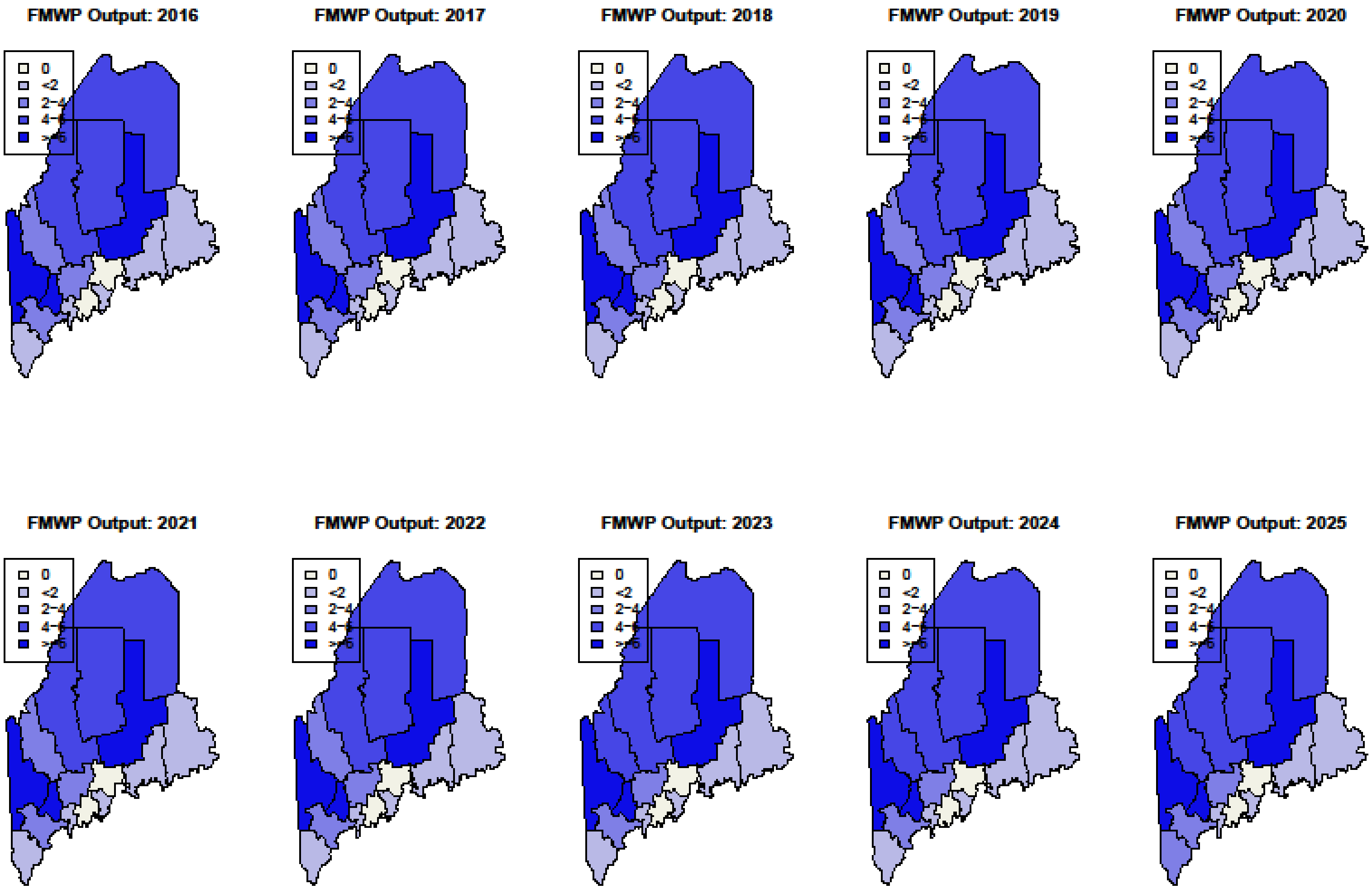

Figure 9. DR.SAGE baseline estimate of the output of finished and miscellaneous wood products (FMSP) by county in thousands of truckloads.

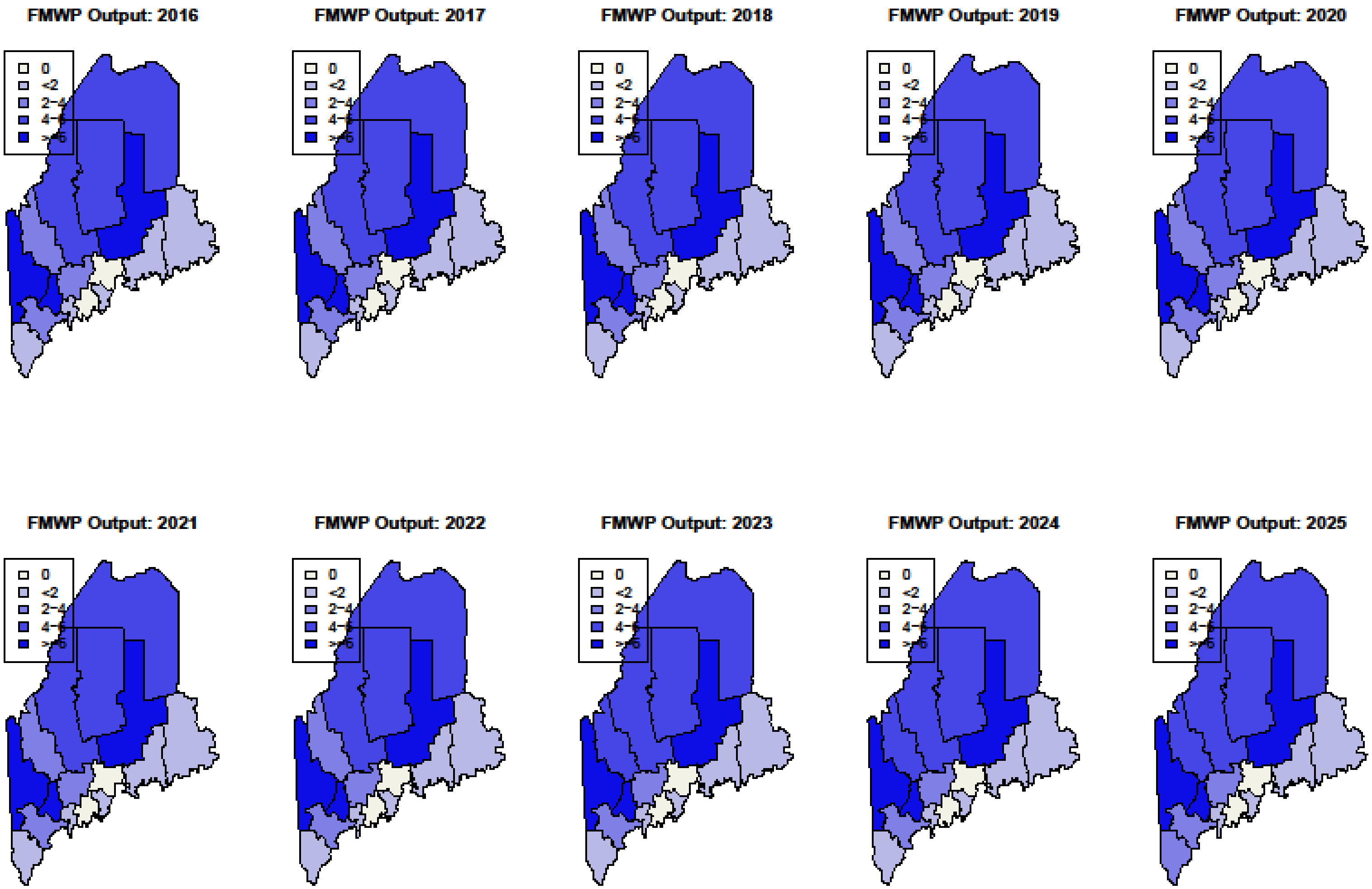

Figure 10. DR.SAGE baseline estimate of the output of finished and miscellaneous wood products (FMSP) by county in thousands of truckloads.

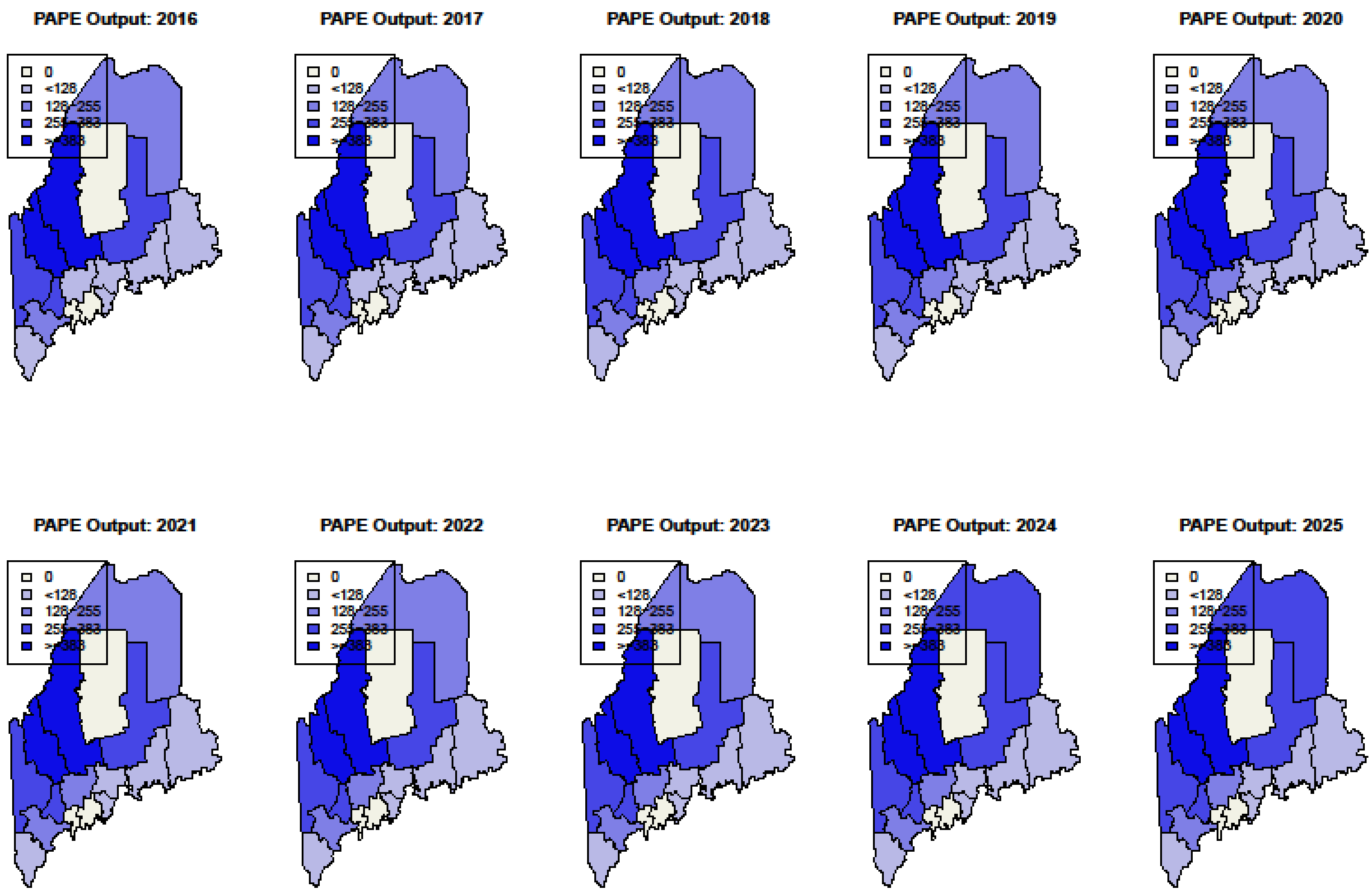

Figure 11. DR.SAGE baseline estimate of the output of paper products (PAPE) by county in thousands of tons.

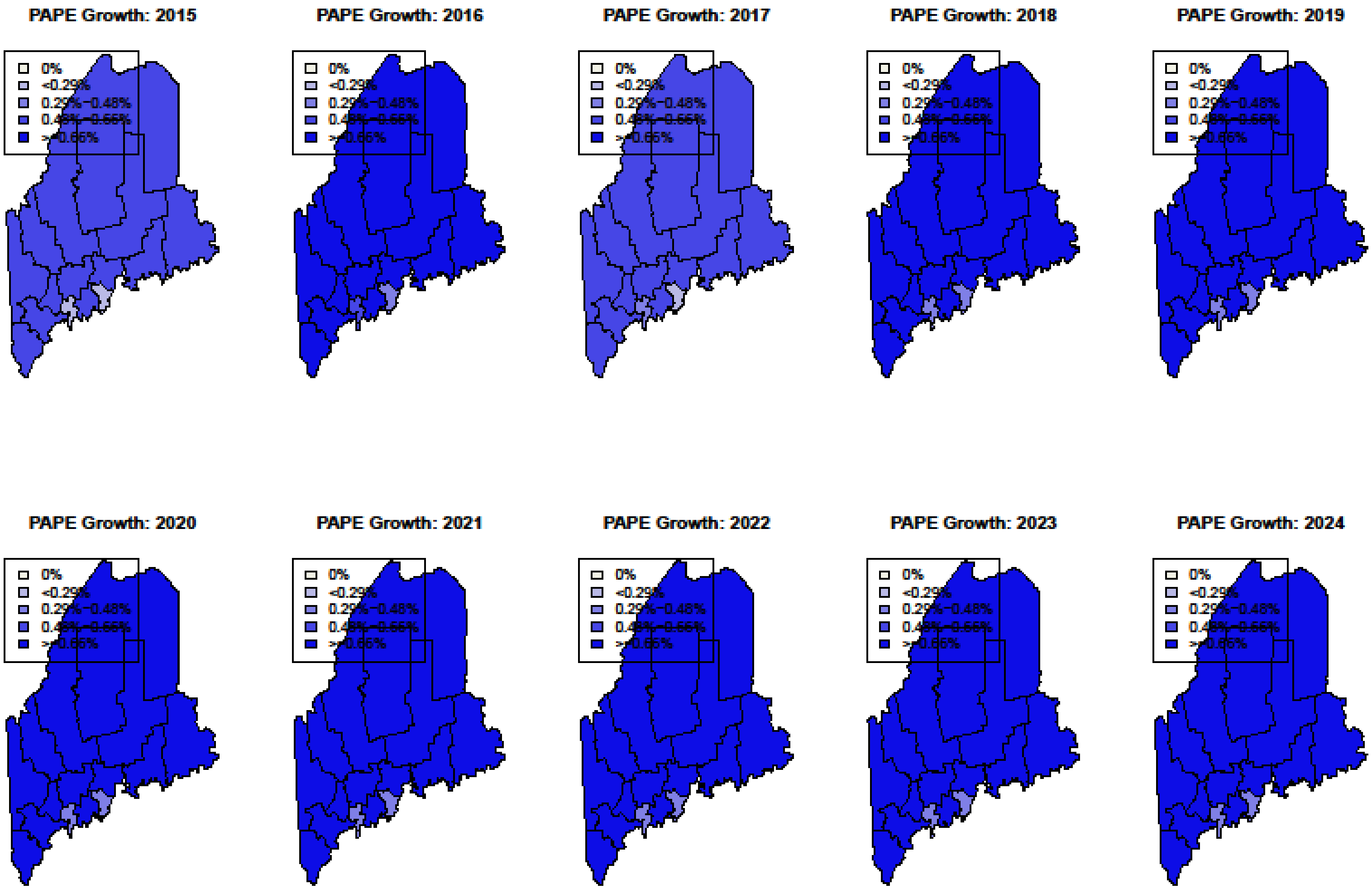

Figure 12. DR.SAGE baseline estimate of the change in paper output (PAPE) by county.

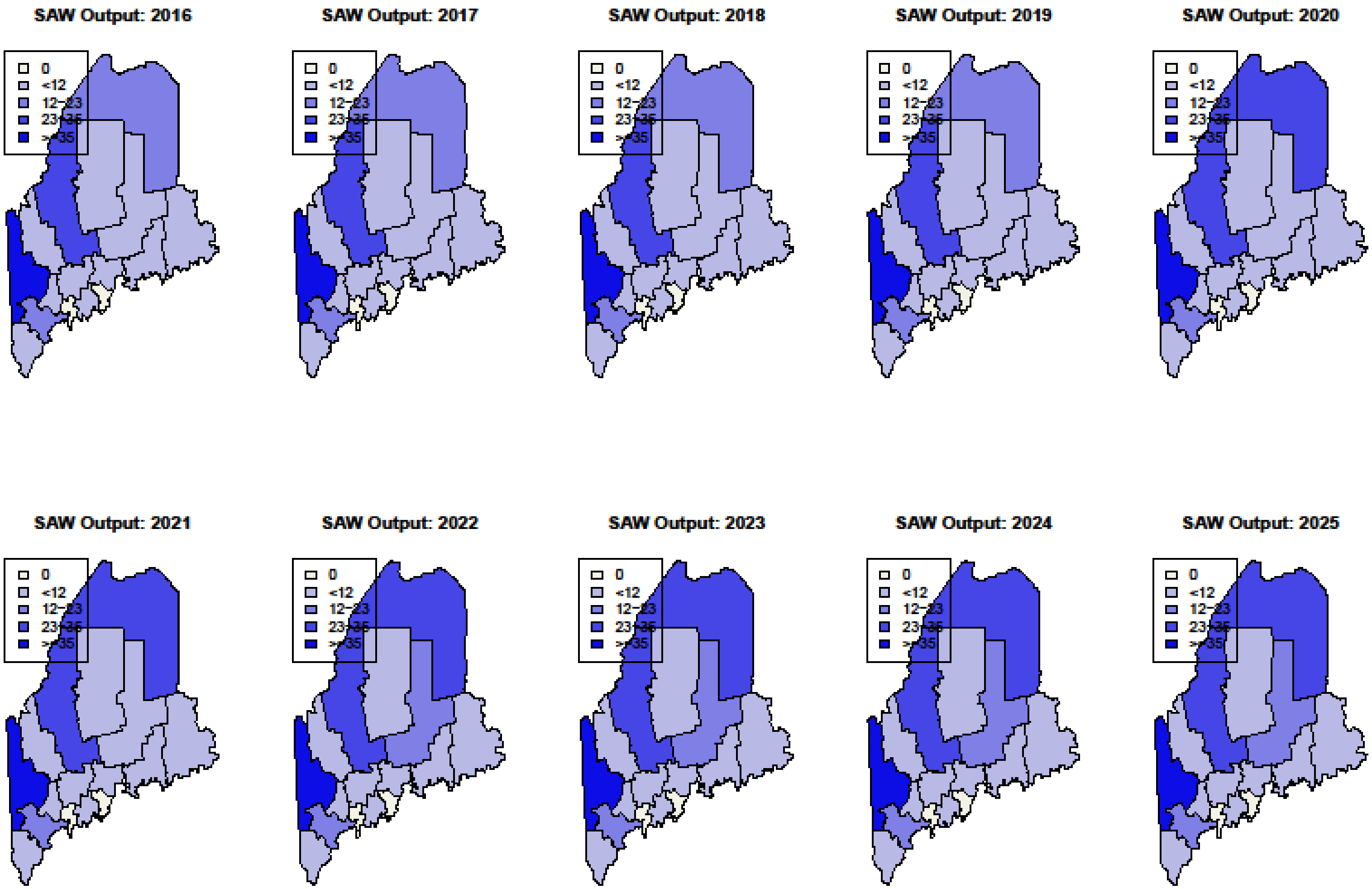

Figure 13. DR.SAGE baseline estimate of the output of sawn wood products (SAW) by county in MMBF.

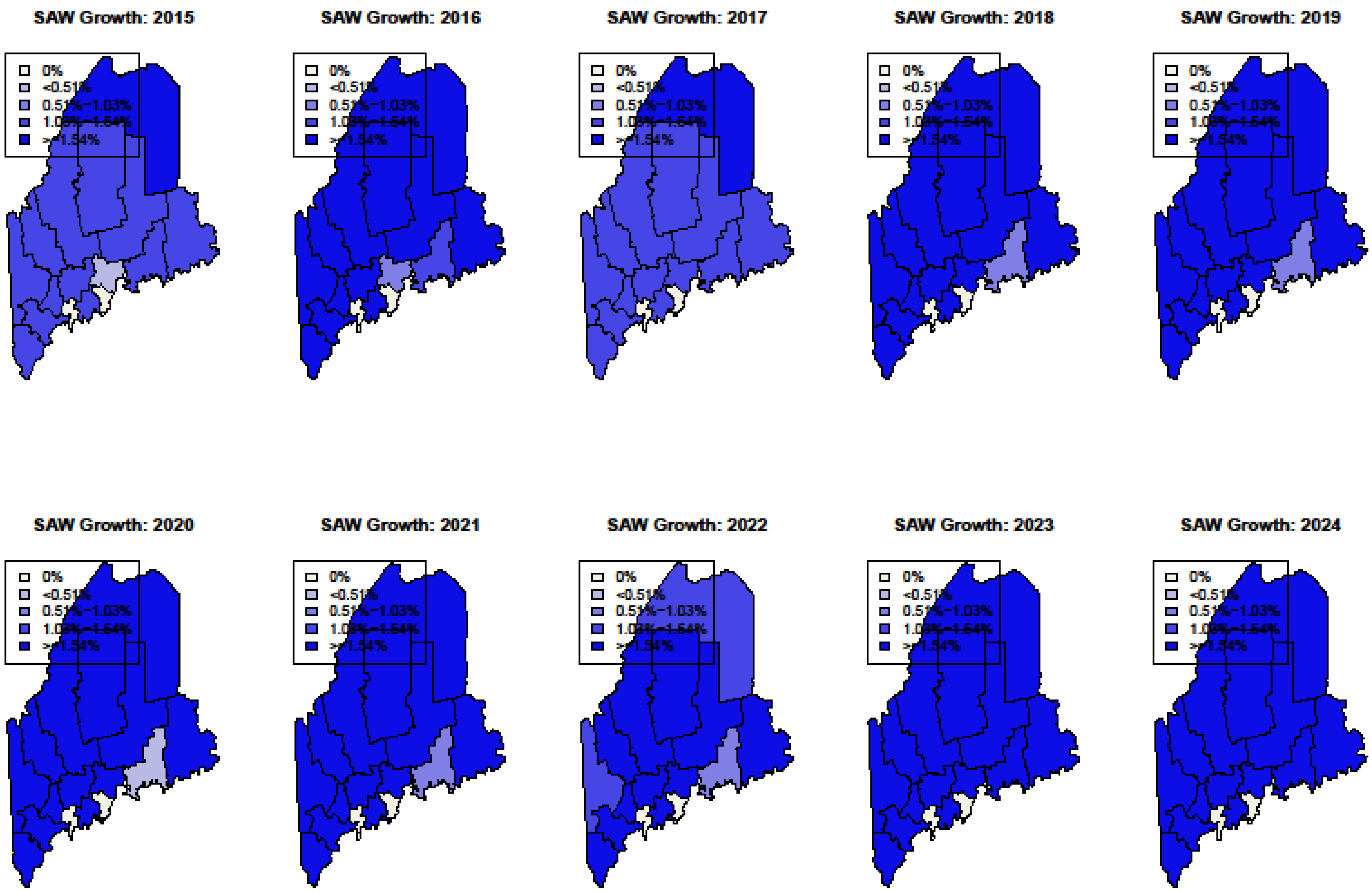

Figure 14. DR.SAGE baseline estimate of the change in sawn wood output (SAW) by county.

CHAPTER 5

DR.SAGE SCENARIOS

5.1. Spruce Budworm

Over the last two centuries there have been numerous records of periodic Spruce Budworm (SBW) outbreaks in Acadian forests (Fraver et al., 2009). While not native to Maine, Fraver et al. (2009) have determined using core increments that the more intense outbreaks escape from Canada into Maine about every 50-60 years. Since the last outbreak in Maine was in the late 1970's, experts expect another outbreak within ten to twenty years (Irland et al, 1988; Fraver et al., 2009).

The Spruce Budworm lays its eggs in the foliage of spruce and fir trees. When the larvae hatch, they feed on the convenient foliage of the trees, preferring new or young foliage. This defoliation has a two-fold effect. While a tree is unlikely to die from hosting SBW for a year, repeated exposure and multiple years of defoliation results in a cumulative defoliation which will increase mortality. Second, live tress experiencing defoliation have their capacity for growth diminished regardless of whether they ultimately die or not. So, by consuming foliage in its larval form the SBW reduces the photosynthetic ability of fir and spruce species, possibly to the point of mortality. Given the importance of the FPI (supports 4% of GDP and Employment, Table 10) and the prominence of spruce and balsam fir in Maine (roughly 40% of Maine's trees, Table 21), it is reasonable to want to understand the impacts of another outbreak of SBW on the forest products industry and its resultant effect on the state's economic health.

5.1.1. Implementation of Spruce Budworm infestations in the DR.SAGE model

To address this desire, I incorporated Spruce Budworm mechanics into the ecological and spatial allocation modules of the DR.SAGE model. I simulated an infestation coming into Maine from Canada, by assigning annual defoliation rates to stands above 44°50'N (Chen et al., 2017). These northern stands are subjected to four different scenarios of SBW intensity: 10 years of no, moderate, heavy, or severe outbreak beginning in 2020 (Irland et al., 1988). These intensities correspond with annual defoliation rates of 0%, 33%, 67%, and 100%, respectively. Cumulative defoliation is simply the number of years since the start of the outbreak times the annual rate e.g. in year 3 of the outbreak cumulative defoliation will be 0%, 100%, 200%, and 300%, respectively.

Using Chen et al.'s functional estimates for mortality and growth reduction based on cumulative defoliation ($CDEF$), I added the following equations to the Growth module

$$P(mort_{stnd}) = \left[\frac{1}{1 + exp(1.825 + 0.000266 * Vol_{stnd} - 0.0154 * \%SW_{stnd} * CDEF_{stnd})} - \frac{1}{1 + \exp(1.825 + 0.000266 * Vol_{stnd})}\right]\left(\frac{1}{1 + exp(5.169 - 0.051 * HT_{stnd})}\right)$$

$$stock_{p,SW,stnd} = \left(1 - P(mort_{stnd})\right) * stock_{p,SW,stnd}$$

where the first term is defoliation-based mortality, the second term is base mortality, and the final term is the probability of being in the possible mortality group. I included the base mortality term (not found in Chen et al., 2017) because growth in the DR.SAGE model is already mortality inclusive (Appendix C), and failing to add this term would create additional mortality in all SBW scenarios regardless of any defoliation. $Vol_{stnd} = \sum_{pg} stock_{pg,stnd}$ is the total timber volume in a stand (Mcu.ft.), $\%SW_{stnd}$ is the proportion of softwoods in the stands and $CDEF_{stnd}$ is the total, cumulative amount of defoliation the tree has experienced. Chen et al.'s equations actually include separate coefficients for the proportion of balsam and spruce in their versions of Eqs. 4X, 4Y. However, the coefficients for both species in both equations were very similar, so I averaged them to better reflect the combined softwood representation of DR.SAGE. Spruce and fir also represent over 80% of the softwood in Maine (Table 21), so I reduced Chen et al.'s equations to accept $\%SW_{stnd}$. HT_{stnd} is the dominant height in the stand, for which I assumed a height of 60ft for all stands because growth in the DR.SAGE model is volume dependent, not size dependent (height and DBH).

To reflect the diminished growth in surviving trees, the following equation is used

$$k^*_{stnd} = k_{stnd} - 0.000009 * \%SW_{stnd} * CDEF_{stnd}$$

k^*_{stnd} is used in placed of k_{stnd} in the growth equation (Eq. 10) without any other modification. Chen et al.'s equation contains a number of other terms which are simply combined into k_{stnd} for simplicity because the only thing changing between scenarios in a given stand is the defoliation level (2017). After the SBW diminished wood stock is grown (Eq. 10), the mortality is added back in so that it is available for harvest in the Spatial allocation module. Within the spatial allocation, a minimum of $salvage * 100\%$ of the budworm mortality is harvested first from any affected stands. If the market does not demand this level of supply, $SBWslack_{SW,stnd}$ acts as an escape valve which allows SBW mortality to remain unharvested, but at a penalty to the objective (the supply price of the dead trees to be salvaged is paid no matter what, representing the loss to landowners). After the spatial allocation, all SBW mortality, harvested or not, and any additional harvesting over SBW mortality are removed from the stock.

$$(1 - cull) * salvage * P(mort_{stnd}) * stock_{p,SW,stnd} \leq Xi_{p,SW,stnd} + SBWslack_{p,SW,stnd}$$

$$stock_{p,SW,stnd} = Stock_{p,SW,stnd} - \max\left(P(mort_{stnd}) * stock_{p,SW,stnd}; X_{p,SW,stnd}/(1 - cull)\right)$$

This new timber inventory is then adjusted based on the next year's cumulative defoliation.

5.1.2 Impacts of Spruce Budworms outbreaks in Northern Maine

5.1.2.1. Softwood Sawlog Inventory Impacts

Given the mechanism of spruce budworm, there was a strong mortality trend in the affected stands. As expected, SBW related mortality increased with the severity of the SBW infestation (Fig. 25). Similarly, annual SBW mortality from SBW was initially highest for the severe outbreak. However, due to continued high levels of consumption in a severe outbreak, the extreme dieback in softwood early on reduced the potential for mortality later as the proportion of softwood fell (Fig. 26).

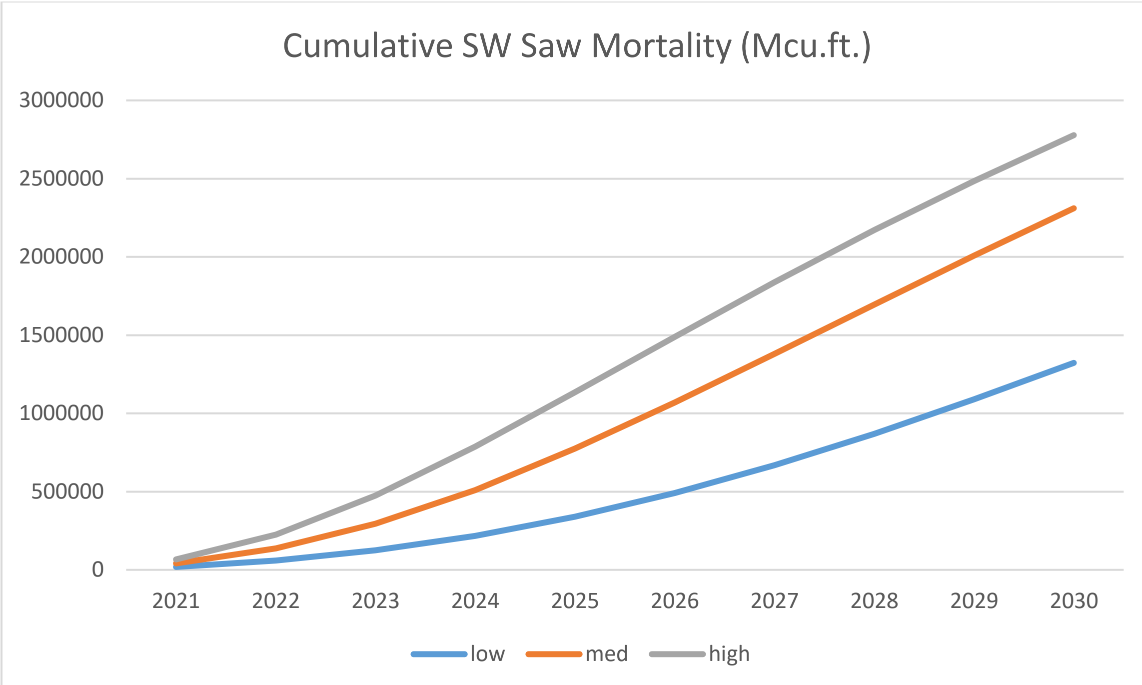

Figure 15. Total cumulative mortality caused by varying levels of SBW infestation.

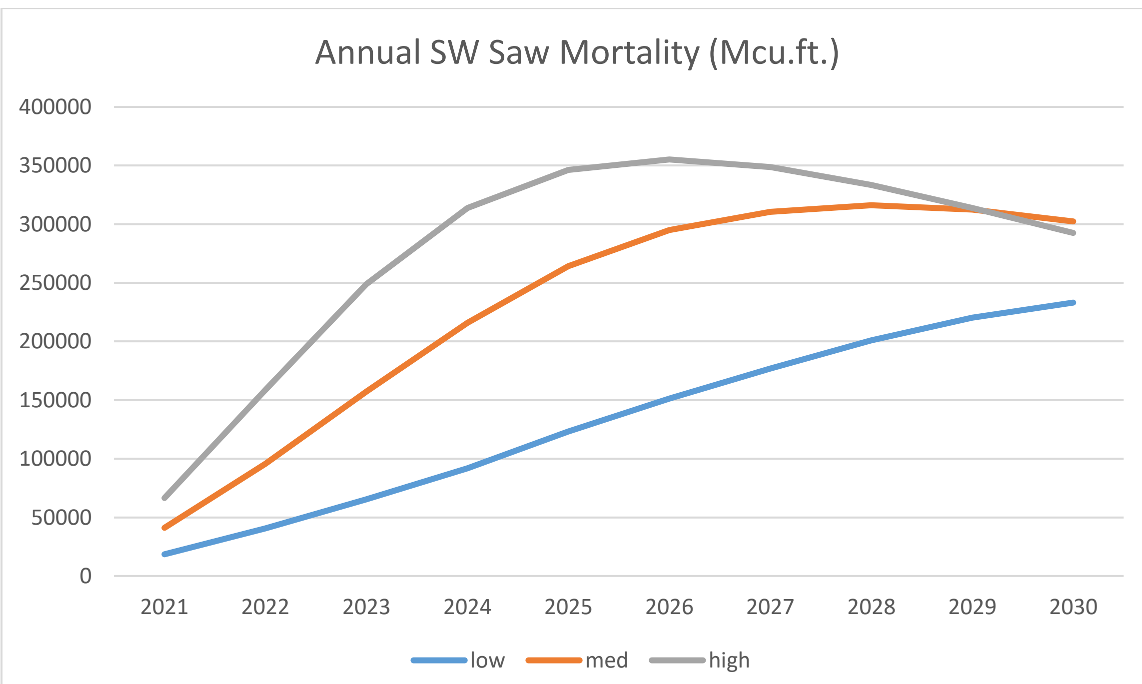

Figure 16. Annual mortality caused by varying levels of SBW infestation.

Without any SBW outbreak in the next 25 years, Maine's softwood timber stock will remain stable, increasing slightly at first given Maine's current growth-to-removals ratio and beginning to decline as demand for forest products increases with population and GDP and outpaces the forest's growth (Fig. 27). This is clear from the harvest percentage, which continually increases despite the initial increase in stock (Fig. 28). The presence of even a moderate outbreak had a strong effect on softwood sawlog stock, resulting in about one billion cubic feet lost by the end of the outbreak. If Maine experienced a severe outbreak, the expected loss of softwood sawlog more than doubled to over two billion cubic feet (Fig. 27). This represented a 5% and 20% loss, respectively, from the initial forest inventory in 2015 while BAU would suggest a 5% increase from the initial stocking (Fig. 29). In all four scenarios, the stock begins (or continues) to decline after 2030. In the three SBW scenarios, this decline was much steeper due to the diminished growth potential from the mortality in the previous decade (Fig. 29). So, without any structural changes, a SBW outbreak may cause long term issues with forest stock. Irland et al. (1988) point out that mills and other wood consumers will attempt to substitute for other species in these scenarios; recycling and technological advancements may decrease the future wood requirements of individual goods, as well.

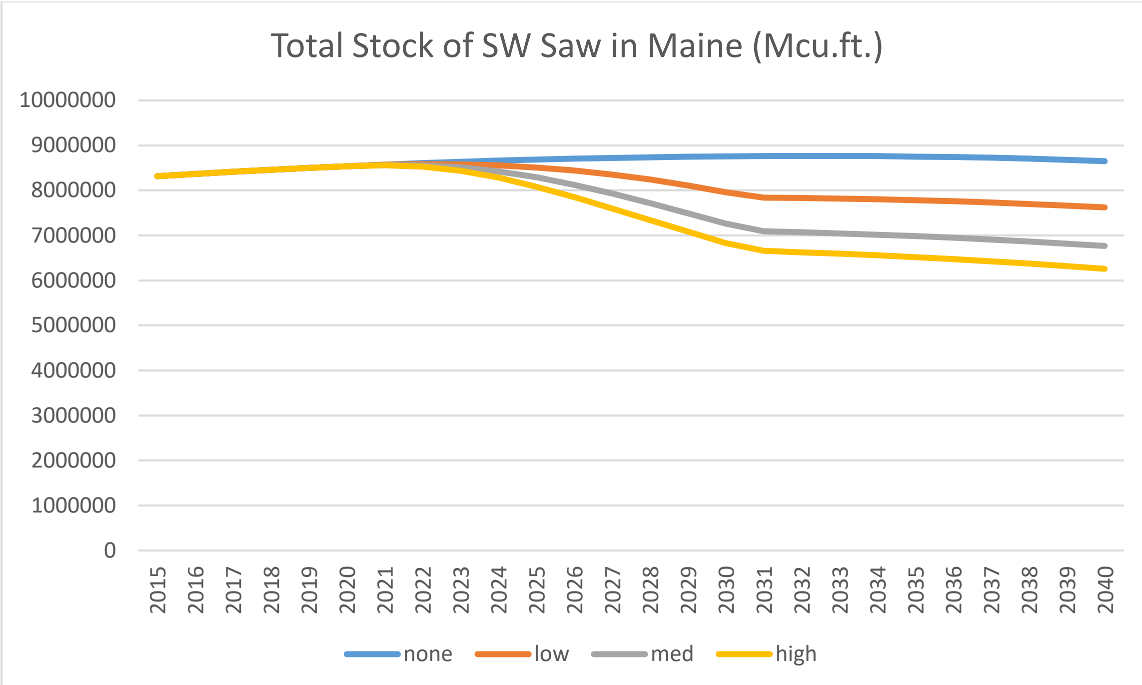

Figure 17. The annual softwood timber stock in Maine through different levels of SBW outbreaks.

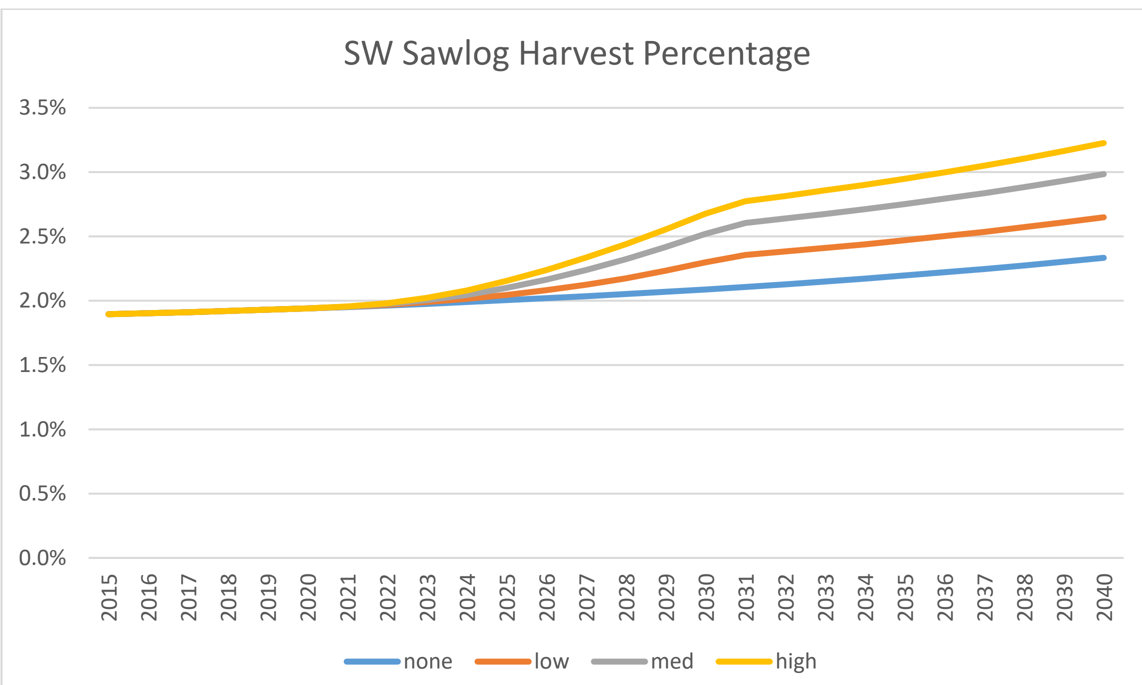

Figure 18. The annual proportion of softwood saw logs harvested from the total stock in Maine.

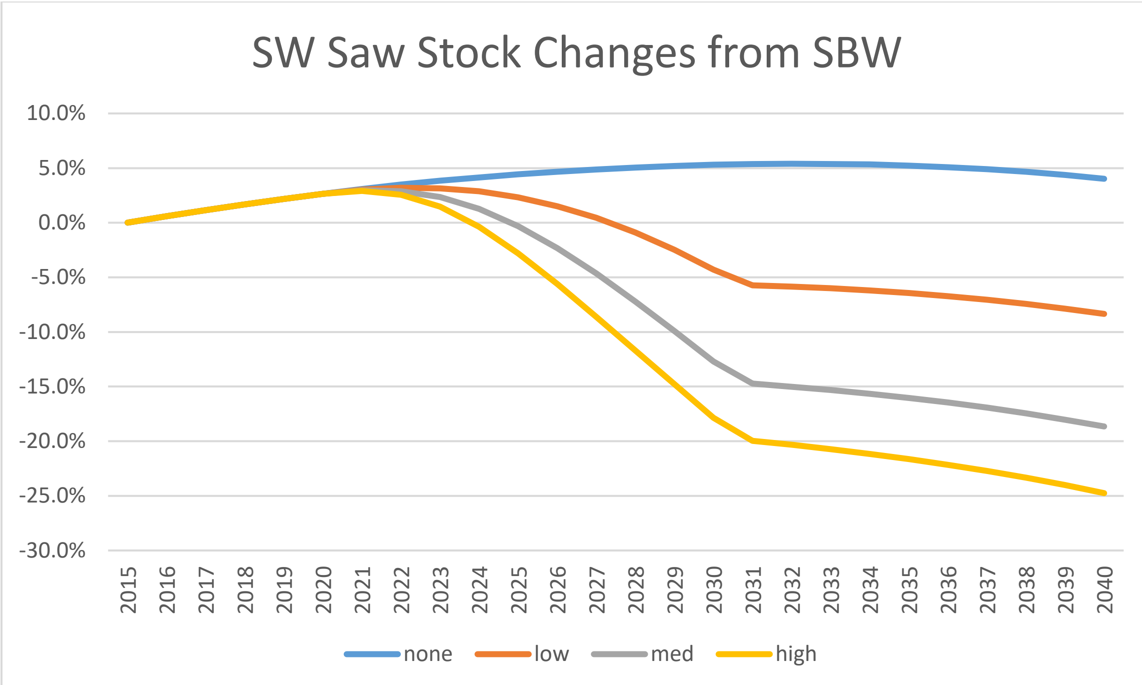

Figure 19. The percent difference in the current stock from the initial model stock under the effects of SBW.

5.1.2.2. Economic Impacts

Regardless of the level of mortality, SBW outbreaks appear to have almost no impact on economic outcomes. The initial demand for all timber products in the model is about 600 million cubic feet, which is only about 1.4% of Maine's 43 billion cubic foot timber stock. For softwood sawlogs, the harvest percentage is higher but still under 2% (Fig. 29), so even the loss of one to two billion cubic feet leaves a lot of wood available to harvest. As Figure 29 shows, even with a 25% loss from the initial stock and an increase in population driven demand, the harvest proportion of softwood sawlogs is still under 3.25%.

In the DR.SAGE model, the harvest level is mandated to include half of the SBW mortality as salvage. While spruce budworm mortality affected the available stock, it had little impact on supply and demand. Since Maine's forests are vast and there was no price mechanism imbedded in the model, the mandate only incurs additional transportation and harvesting costs by reallocating harvests. These additional costs were insufficient to affect the production of pulp, paper, or lumber by more than a fractional amount. This result could be drastically improved by incorporating a price mechanic for the available salvage wood. This would actively influence demand but also capture the losses that landowners face. In short, the DR.SAGE model is a demand driven model and a supply shock that doesn't also include some link to demand will produce minimal changes. In the next section, I modeled a demand driven scenario, showing a much different outcome. Other work has found that infestations, such as spruce budworm or mountain pine beetle, generally result in a decline in GDP (Chang et al., 2012; Corbett et al., 2015). This is largely due to a long-term decline in forest industry output. In many areas with infestations, harvest will be increased to capture mortality. After a time however, the reduce stock puts a strain on the forest products industry. Reformatting the budworm scenarios to have a demand link and a longer horizon would likely have the DR.SAGE model mirroring these other results. More work on how SBW mortality influences mill production choices and the resulting economic impacts could be beneficial; as Irland et al. note, "they have been little studied so far."

5.2. Meeting the Other FOR/Maine Objective

Given the prominence of forest products in Maine, many stakeholders have visions for the future of the industry. One such initiative is the FOR/Maine plan. One facet of this plan is to increase the economic contribution of the FPI to Maine by 40%, from \$8.5B to \$12B, by 2025. I used the DR.SAGE model to analyze Maine's path to this goal and how Maine can use its forest and increase its exports to do so. In the following scenarios, I looked at the real growth in each

FPI sector necessary to meet the FOR/Maine goal and how that growth influences purchase flows in Maine. This real growth is driven by a growth in external demand.

5.2.1 Driving Toward the FOR/Maine Objective

From 2011 to 2016, Maine experienced a 2.86% per annum nominal growth rate and a 0.65% real growth rate in GDP. Inflation in Maine has historically been around 1.5%, but in recent years it has been greater than 2%. Finally, Maine has a slow population growth, only around 0.2% per year. Because contribution studies report nominal values by default, each of these factors must be accounted for in the DR.SAGE model to accurately determined the real growth needed to achieve a 40% increase. Assuming 2% inflation and 0.2% population growth annually, Maine's economy would grow roughly 21.6% to 10.4B from 2016 to 2025. The following table describes the required real growth in each FPI sector to make up the remainder and reach the $12B contribution benchmark under variable minimum growth requirements. That is, I set some minimum threshold for growth by 2025 for all the sectors. Since the paper industry is such a large component of the FPI, the path that requires the least amount of total annual growth across the FPI is to assume the paper sector is responsible for all the growth in the FPI. However, this is an unrealistic assumption for many reasons. Foremost among these are that this assumption unfairly burdens the paper sectors and its workers in a time when paper demand is uncertain. Similarly, it discounts all the other sectors which will undoubtedly experience some real growth. Altogether, if each FPI sector grew the same amount each year between 2016 and 2025, they would need to achieve approximately 1.62% real annual growth. This is 2.5 times the real growth observed in Maine.

I looked at four growth scenarios for reaching $12B in FPI contributions, each with a specified level of minimum growth participation. The first imposes no restrictions, assuming no minimum growth requirement. This yields the situation above where the paper sector bears the entire growth burden simply because a 1% increase in the paper sector yields as much increase for the FPI overall as a 2% increase in all the other FPI sectors together. I mitigated this in the other scenarios, but the shortest path to meet the FOR/Maine goal will always rely on paper growth. The second scenario assumes a minimum growth equal to that observed in Maine, 0.65% per year or 6% by 2025. Growth here is still dominated by paper, but all the other sectors grow at least at an average rate. The third scenario assumes the minimum growth participation is moderate. Each FPI sector must grow at 1.17% per year, or 11% by 2025. Finally, the last scenario assumes that each FPI sector grows evenly, achieving 1.62% annual growth. The entire industry uniformly increases by 15.6% by 2025.

	Minimum participation in annual growth for each FPI sector			
	None 0%	**Regular 6% (0.65%/yr)**	**Moderate 11% (1.17%/yr)**	**Full 15.6% (1.62%/yr)**
Pulp Products	0.34%	0.85%	1.26%	1.62%
Paper	2.46%	2.15%	1.88%	1.63%
Sawmills	0.59%	1.00%	1.33%	1.62%
Wood Products	0.33%	0.84%	1.26%	1.62%
Plywood and Veneer	0.23%	0.79%	1.23%	1.62%
Harvesting	0.25%	0.80%	1.23%	1.62%
Wood Furniture	0.12%	0.72%	1.20%	1.62%
Bioelectric	0.07%	0.69%	1.19%	1.62%

Table 26. Real annual growth rates from 2016 for each sector required to achieve a $12B forest economy in Maine by 2025.

I additionally assumed that this growth comes purely from increase exports. This is for two reasons. First, 93% of Maine's forest products are exported, so the assumption is realistic. Second, if the growth came from inside of Maine, it would have to be supported by growth in other Maine industries. In that case, the model would more accurately answer how Maine's FPI grows when other Maine sectors grow, instead of the reverse. The growth in the FPI could also come about from technology shifts favoring FPI outputs. However, technical change is hard to predict and to model and, in any case, the changes would only provide the full benefit to Maine overall if Maine's FPI goods were substituted for imports, not other Maine produced goods.

5.2.2. FOR/Maine Update Results

While the most obvious impacts of an expansion of Maine's FPI are within the FPI sectors, this growth also generates smaller impacts across the economy. Overall, the FOR/Maine expansion has a slightly positive impact on Maine's economy, as measured by GDP. Given the initial increase already estimated by the DR.SAGE baseline, Maine's GDP may increase 0.2%-0.5% over the next ten years (Table 27). This is a smaller than anticipated increase. Very simply, the FPI represents around 5% of Maine's GDP and I was modeling a real 16% increase in production, which would yield a 0.8% increase in real GDP. This implies that the full GDP increase from FPI growth under the FOR/Maine scenarios is offset by changes in other sectors.

	Percent change in Maine's 2025 GDP from the baseline estimate			
	none	**reg**	**mod**	**full**
2016	-0.01%	-0.01%	0.00%	-0.01%
2017	-0.01%	-0.01%	0.00%	-0.01%
2018	0.00%	0.00%	0.00%	0.00%
2019	0.00%	0.00%	0.00%	0.00%
2020	0.00%	0.00%	0.01%	0.01%
2021	0.00%	0.00%	0.01%	0.01%
2022	0.00%	0.01%	0.01%	0.01%
2023	0.04%	0.05%	0.05%	0.06%
2024	0.03%	0.04%	0.04%	0.05%
2025	0.03%	0.04%	0.04%	0.05%

Table 27. Additional change in Maine's GDP from expansion to meet the FOR/Maine contribution objective.

I estimate most sectors in Maine would contract slightly and fall in price. Most of these would only experience an average 0.1% drop in 2025 output and price compared to the baseline 2025 estimates (Table 28).

	Percent change in 2025 prices of non-FPI goods from the baseline estimate					**Percent change in 2025 output of non-FPI goods from the baseline estimate**				
	base	**none**	**reg**	**mod**	**full**	***base***	**none**	**reg**	**mod**	**full**
FORE	*22.21%*	0.55%	1.40%	2.13%	2.79%	*10.70%*	0.70%	1.56%	2.28%	2.94%
22-UTIL	*17.27%*	0.40%	0.51%	0.41%	0.47%	*8.82%*	0.41%	0.40%	0.43%	0.34%
SUPP	*20.78%*	-0.14%	0.06%	0.27%	0.47%	*6.58%*	-0.11%	0.07%	0.28%	0.47%
FOREXT	*22.34%*	0.17%	0.19%	0.17%	0.15%	*4.24%*	0.18%	0.19%	0.17%	0.16%
55-MGMT	*18.35%*	0.14%	0.14%	0.15%	0.15%	*8.11%*	0.09%	0.11%	0.08%	0.08%
42-WHOL	*-9.40%*	0.23%	0.17%	0.14%	0.18%	*40.68%*	0.21%	0.25%	0.25%	0.25%
PINC	*22.50%*	0.03%	0.07%	0.11%	0.15%	*4.59%*	0.04%	0.08%	0.11%	0.15%
DOMEXT	*22.33%*	0.09%	0.10%	0.09%	0.07%	*4.23%*	0.10%	0.10%	0.09%	0.08%
LABR	*22.54%*	0.05%	0.06%	0.06%	0.07%	*4.44%*	0.06%	0.06%	0.07%	0.07%
53b-RENT	*20.94%*	0.03%	0.03%	0.04%	0.02%	*5.98%*	0.02%	0.00%	-0.01%	-0.01%
SLTAX	*22.72%*	0.04%	0.05%	0.04%	0.04%	*4.56%*	0.07%	0.06%	0.05%	0.05%
FDTAX	*22.72%*	0.04%	0.05%	0.04%	0.04%	*4.56%*	0.07%	0.06%	0.05%	0.05%
TAR	*22.72%*	0.04%	0.05%	0.04%	0.04%	*4.56%*	0.07%	0.06%	0.05%	0.05%
HOHO200	*21.35%*	0.00%	0.01%	0.01%	0.02%	*5.75%*	0.01%	0.01%	0.02%	0.02%
HOHO150	*22.04%*	-0.01%	-0.01%	0.00%	0.00%	*5.20%*	-0.01%	-0.01%	0.00%	0.00%
ENTR	*22.65%*	0.00%	0.00%	-0.01%	-0.01%	*4.49%*	0.00%	0.00%	-0.01%	-0.01%
81-OTHR	*21.21%*	-0.02%	-0.03%	-0.02%	-0.02%	*5.24%*	-0.02%	-0.03%	-0.02%	-0.02%
OPTI	*22.30%*	-0.01%	-0.02%	-0.02%	-0.02%	*4.55%*	0.00%	-0.01%	-0.02%	-0.02%
HOHO	*22.31%*	-0.04%	-0.05%	-0.05%	-0.04%	*4.20%*	-0.04%	-0.05%	-0.05%	-0.04%
HOHO40	*22.01%*	-0.06%	-0.07%	-0.06%	-0.06%	*4.92%*	-0.04%	-0.05%	-0.05%	-0.04%
HOHO50	*21.26%*	-0.06%	-0.06%	-0.06%	-0.05%	*5.68%*	-0.03%	-0.03%	-0.03%	-0.02%
HOHO100	*21.68%*	-0.06%	-0.06%	-0.06%	-0.05%	*5.45%*	0.01%	0.01%	0.02%	0.02%
21-MGOE	*21.66%*	-0.04%	-0.06%	-0.07%	-0.09%	*4.79%*	-0.04%	-0.06%	-0.07%	-0.08%
53a-REAL	*22.21%*	-0.06%	-0.07%	-0.07%	-0.06%	*4.38%*	-0.05%	-0.07%	-0.06%	-0.06%
61-EDUC	*21.83%*	-0.07%	-0.08%	-0.08%	-0.07%	*4.62%*	-0.07%	-0.08%	-0.08%	-0.07%
HOHO70	*21.04%*	-0.08%	-0.09%	-0.08%	-0.08%	*5.91%*	-0.01%	-0.02%	-0.01%	-0.01%
GOVTI	*22.26%*	-0.07%	-0.08%	-0.08%	-0.08%	*4.19%*	-0.07%	-0.08%	-0.08%	-0.08%
52-FINA	*19.83%*	-0.09%	-0.10%	-0.09%	-0.09%	*6.57%*	-0.08%	-0.10%	-0.09%	-0.09%
HOHO30	*21.97%*	-0.09%	-0.11%	-0.10%	-0.10%	*4.78%*	-0.08%	-0.09%	-0.09%	-0.09%
GOVT	*14.99%*	-0.10%	-0.12%	-0.11%	-0.11%	*11.61%*	-0.06%	-0.08%	-0.07%	-0.07%

Table 28. Continued

71-RECR	*20.89%*	-0.12%	-0.14%	-0.13%	-0.13%	*5.50%*	-0.11%	-0.13%	-0.12%	-0.12%
51-INFO	*18.61%*	-0.13%	-0.14%	-0.14%	-0.14%	*7.56%*	-0.08%	-0.10%	-0.09%	-0.09%
54-PROF	*16.50%*	-0.12%	-0.15%	-0.14%	-0.10%	*9.57%*	-0.05%	-0.05%	-0.05%	-0.08%
72-TOUR	*19.79%*	-0.13%	-0.16%	-0.15%	-0.14%	*6.49%*	-0.13%	-0.14%	-0.14%	-0.13%
92-ADMN	*21.50%*	-0.12%	-0.15%	-0.15%	-0.15%	*5.00%*	-0.13%	-0.15%	-0.16%	-0.16%
HOHO15	*21.59%*	-0.14%	-0.16%	-0.15%	-0.15%	*4.88%*	-0.13%	-0.15%	-0.15%	-0.14%
FEDI	*22.19%*	-0.13%	-0.15%	-0.15%	-0.15%	*4.17%*	-0.13%	-0.15%	-0.15%	-0.15%
FED	*21.87%*	-0.14%	-0.17%	-0.16%	-0.16%	*4.77%*	-0.14%	-0.16%	-0.16%	-0.15%
62-HEAL	*18.37%*	-0.15%	-0.17%	-0.17%	-0.16%	*7.68%*	-0.14%	-0.16%	-0.16%	-0.15%
HOHO0	*21.89%*	-0.22%	-0.25%	-0.25%	-0.24%	*4.42%*	-0.21%	-0.25%	-0.24%	-0.24%
FEDD	*21.92%*	-0.26%	-0.30%	-0.30%	-0.29%	*4.49%*	-0.26%	-0.30%	-0.30%	-0.24%
44-RTAL	*4.48%*	-0.30%	-0.31%	-0.31%	-0.30%	*21.97%*	0.02%	-0.01%	-0.01%	0.00%
GOVTE	*21.86%*	-0.28%	-0.33%	-0.32%	-0.32%	*4.59%*	-0.28%	-0.33%	-0.32%	-0.32%
23-CONS	*18.06%*	-0.32%	-0.38%	-0.34%	-0.33%	*7.93%*	-0.07%	-0.08%	-0.10%	-0.11%
MACH	*22.28%*	-0.24%	-0.30%	-0.34%	-0.37%	*4.40%*	-0.24%	-0.30%	-0.34%	-0.37%
32-MMFG	*17.07%*	-0.35%	-0.41%	-0.40%	-0.40%	*9.05%*	-0.34%	-0.39%	-0.39%	-0.39%
CAP	*19.91%*	-0.36%	-0.41%	-0.40%	-0.40%	*6.59%*	-0.36%	-0.41%	-0.41%	-0.40%
INV	*22.13%*	-0.38%	-0.44%	-0.43%	-0.43%	*4.20%*	-0.38%	-0.44%	-0.43%	-0.43%
11-AGFH	*21.00%*	-0.49%	-0.56%	-0.56%	-0.55%	*5.37%*	-0.49%	-0.56%	-0.55%	-0.54%
31-NDMFG	*17.20%*	-0.50%	-0.57%	-0.56%	-0.55%	*8.90%*	-0.49%	-0.57%	-0.56%	-0.55%
33-DMFG	*20.15%*	-0.55%	-0.63%	-0.62%	-0.61%	*6.24%*	-0.55%	-0.63%	-0.62%	-0.61%
48-TRWH	*-24.38%*	-1.59%	-1.58%	-1.57%	-1.60%	*69.43%*	1.98%	2.02%	2.00%	2.02%

Table 28. Additional percent change in non-FPI goods prices and outputs under the FOR/Maine scenarios. Base represents the final change in 2025 from 2016 in the baseline scenario. The other columns represent the additional change from the corresponding year in the baseline.

Others which more directly compete with the FPI for inputs like land, such as agriculture (11-AGFH), capital (CAP), construction (21-CONS), and manufacturing (31-NDMFG, 32-MMFG, 33-DMFG), experience more marked declines. Prices of these goods fall 0.3%-0.6% and outputs decline 0.1%-0.6%. Conversely, sectors which complement the FPI sectors experience additional growth. Forestry (FORE), harvesting support (SUPP), utilities (22-UTIL), labor and profit (LABR, PINC), and land lease (53b-RENT) experience additional growth by supplying inputs to the FPI sectors. These effects follow the same pattern across scenarios, slowly increasing in magnitude as the minimum growth participation increases. Any matched increases in prices and output suggest that the additional growth in these sectors is driven purely by the external demand increases rather than additional spatial reallocation. In these cases, growth is uniform across counties. In each of the following tables, the total growth of any price or output between 2016 and 2025 for each scenario can be conservatively estimated by adding the adding the corresponding italic base entry and the scenario entry.

5.2.3. Harvest Changes

Much like the non-FPI sectors which supply inputs to the FPI benefit from the FOR/Maine expansion, the production and prices of wood types is positively affected. As more FPI sectors contribute to the expansion, the additional amount of harvest increases. This is likely because the paper sector (PAPE) consumes a relatively small amount of raw wood. Sawmills (SAW), biomass plants (BIOM), and pulp mills (PULP) are much more active in the raw wood markets, so their expansion is a stronger driver of impacts in wood markets. The total 2025 harvest will be 1.4%-5.3% larger under FOR/Maine growth scenarios than in the 2025 baseline (Table 29). This is a gradual expansion as FPI mills add new capacity for external demand each year. When no minimum growth is required and paper dominates the expansion, softwood and hardwood pulp (ComSWPlp, ComHWPlp) expand about 2% while other wood types only expand less than 1% (Table 39). As participation becomes more diverse, the harvest increase becomes more uniform with biomass products (ComSWBio, ComHWBio, NonComBio) increasing over 4% and all other increasing over 5% (Table 30). The total harvest proportion in Maine increases from 1.7% to 1.8% in the later years of the full and moderate participation scenarios.

	Percent change in Maine’s 2025 total harvest from the baseline estimate				
	base	**none**	**reg**	**mod**	**full**
2016	*0.00%*	0.00%	0.00%	0.00%	0.00%
2017	*0.48%*	0.00%	0.02%	0.16%	0.29%
2018	*0.91%*	0.02%	0.33%	0.61%	0.86%
2019	*1.35%*	0.18%	0.69%	1.10%	1.46%
2020	*1.82%*	0.38%	1.05%	1.60%	2.08%
2021	*2.29%*	0.58%	1.42%	2.10%	2.70%
2022	*2.77%*	0.78%	1.79%	2.60%	3.33%
2023	*3.24%*	1.00%	2.17%	3.12%	3.97%
2024	*3.73%*	1.21%	2.55%	3.64%	4.62%
2025	*4.24%*	1.42%	2.93%	4.15%	5.26%

Table 29. Additional percentage increase in total Maine harvest in 2025 from the 2025 baseline. Base represents the final change in 2025 from 2016 in the baseline scenario. The other columns represent the additional change from the corresponding year in the baseline.

The prices of the raw wood products are similarly driven up by the expansion of the FPI sectors, with increases first in pulp wood and then in the other wood classes as participation increases. The matching increases in prices and output suggest that the additional growth in the harvest is driven purely by the external demand increases rather than additional spatial reallocation. Despite a high level of spatial flexibility, there is little substitution because most heavily harvested stands have significant excess capacity. These increases in the wood markets are driven both by increased inputs to FPI sectors, but also directly by increased log exports (30%-70% of the markets for these products).

	Percent change in 2025 wood prices from the baseline estimate					Percent change in 2025 wood harvests from the baseline estimate				
	base	**none**	**reg**	**mod**	**full**	***base***	**none**	**reg**	**mod**	**full**
ComSWBio	*22.44%*	0.75%	2.08%	3.24%	4.29%	*4.31%*	0.75%	2.07%	3.24%	4.29%
ComHWBio	*22.43%*	0.80%	2.07%	3.17%	4.17%	*4.30%*	0.80%	2.07%	3.17%	4.17%
NonComBio	*22.41%*	0.85%	2.21%	3.38%	4.45%	*4.28%*	0.85%	2.21%	3.39%	4.45%
ComSWPlp	*22.29%*	2.25%	3.72%	4.74%	5.67%	*4.19%*	2.25%	3.72%	4.75%	5.67%
ComHWPlp	*22.34%*	1.93%	3.47%	4.63%	5.68%	*4.23%*	1.93%	3.47%	4.63%	5.68%
NonComPlp	*22.39%*	0.93%	2.49%	3.85%	5.09%	*4.27%*	0.93%	2.49%	3.86%	5.09%
ComSWSaw	*22.35%*	1.06%	2.67%	4.07%	5.33%	*4.23%*	1.06%	2.67%	4.08%	5.33%
ComHWSaw	*22.34%*	1.17%	2.74%	4.09%	5.31%	*4.23%*	1.17%	2.74%	4.10%	5.31%
NonComSaw	*22.44%*	0.55%	2.38%	4.07%	5.59%	*4.31%*	0.55%	2.38%	4.07%	5.59%

Table 30. The additional percentage change in wood prices and harvests from the baseline scenario by species x product classes. Base represents the final change in 2025 from 2016 in the baseline scenario. The other columns represent the additional change from the corresponding year in the baseline.

5.2.4. Changes in FPI Output

The largest changes to Maine's economy under the FOR/Maine expansion scenarios are in the FPI sectors since they are directly grown through increased external demand. Representing over two-thirds of the industry, paper (PAPE) expansion dominates all the scenarios except for in the case of full participation (Table 34).

Without any participation from other sectors, the paper sector (PAPE) needs to grow an additional 9.4% by 2025 to meet the FOR/Maine objective. This only falls to an additional 7% growth when all the other FPI sectors participate fully. The price of paper increases an additional 9.2% to 6.9% from the baseline scenario, corresponding to the level of additional output growth (Table 35). The difference between the additional change in output and additional change in price indicates that there is a small amount of additional spatial allocation optimization possible in the paper market due to the increased demand. Generally, the additional growth in Sagadahoc and Know counties is slower than that of the rest of the state.

	Percent change in paper output from the baseline estimates									
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
base	*0.00%*	*0.85%*	*1.50%*	*2.28%*	*3.04%*	*3.82%*	*4.60%*	*5.40%*	*6.18%*	*7.03%*
none	0.00%	0.00%	1.07%	2.20%	3.35%	4.52%	5.70%	6.91%	8.14%	9.35%
reg	0.00%	1.33%	2.33%	3.34%	4.35%	5.37%	6.40%	7.45%	8.53%	9.58%
mod	0.00%	1.16%	2.02%	2.89%	3.77%	4.65%	5.54%	6.44%	7.38%	8.28%
full	0.00%	0.98%	1.72%	2.46%	3.21%	3.96%	4.72%	5.49%	6.28%	7.04%

Table 31. The additional percentage change in final paper output from the 2025 baseline. Base represents the final in 2025 change from 2016 in the baseline scenario. The other columns represent the additional change from the corresponding year in the baseline.

The additional expansion of pulp production (PULP), in contrast, is driven solely by increased demand. There is no real possibility of spatial substitution for the additional output, perhaps because pulp production is only present in three counties, so the output grows uniformly in the three counties in all the scenarios. The pulp sector generally expands beyond the specified increased external demand due to the heavy presence of the paper sector in each scenario. For comparison, finished and miscellaneous wood products (FMWP) and pulp mills (PULP) have identical required growth schedules in each scenario (Table 35). However, additional pulp output (PULP), as an input to Maine's FPI, increases significantly more than additional finished and miscellaneous wood products output (FMWP), an export (Table 34). To meet the FOR/Maine objective, the pulp sector (PULP) will have to grow an additional 1.5%-6.6% by 2025 over the 5.2% baseline increase in output (Table 33).

	Percent change in pulp output from the baseline estimates									
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
base	*0.00%*	*0.62%*	*1.09%*	*1.66%*	*2.23%*	*2.80%*	*3.37%*	*3.96%*	*4.53%*	*5.15%*
none	0.00%	0.00%	0.08%	0.25%	0.45%	0.64%	0.84%	1.04%	1.26%	1.45%
reg	0.00%	0.07%	0.49%	0.91%	1.32%	1.74%	2.16%	2.58%	3.02%	3.43%
mod	0.00%	0.32%	0.92%	1.51%	2.10%	2.70%	3.30%	3.90%	4.52%	5.12%
full	0.00%	0.54%	1.30%	2.05%	2.80%	3.55%	4.32%	5.08%	5.88%	6.64%

Table 32. The additional percentage change in final pulp output from the 2025 baseline. Base represents the final in 2025 change from 2016 in the baseline scenario. Base represents the final change from 2016 in the baseline scenario. The other columns represent the change from the corresponding year in the baseline.

I estimate the output of saw wood (SAW) will need to increase an additional 1.7% to 5.6% over the baseline growth of 14.7% by 2025 in order to meet the FOR/Maine objective (Table 33). This is accompanied by a 1.7% to 5.9% increase in the price of sawn wood (Table 35). This small output/price differential is caused by slower growth in Waldo and Hancock counties.

	Percent change in sawn wood output from the baseline estimates									
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
base	*0.00%*	*1.54%*	*3.01%*	*4.57%*	*6.16%*	*7.79%*	*9.52%*	*11.09%*	*12.84%*	*14.65%*
none	0.00%	0.00%	0.13%	0.33%	0.55%	0.77%	0.93%	1.27%	1.49%	1.70%
reg	0.00%	0.13%	0.47%	0.86%	1.24%	1.63%	1.96%	2.48%	2.87%	3.24%
mod	-0.02%	0.25%	0.73%	1.25%	1.78%	2.30%	2.77%	3.42%	3.95%	4.48%
full	0.00%	0.41%	1.03%	1.67%	2.32%	2.97%	3.56%	4.34%	4.99%	5.63%

Table 33. The additional percentage change in final sawn wood output from the 2025 baseline. Base represents the final in 2025 change from 2016 in the baseline scenario. Base represents the final change from 2016 in the baseline scenario. The other columns represent the additional change from the corresponding year in the baseline.

Biomass electricity (BIOM) has very low additional growth in all scenarios (Tables 34 and 35). Since the increased demand is assumed to come from externally increase demand and biomass electricity (BIOM) is not exported, the sector can only see additional growth naturally through population growth and the other sectors' heightened expansions. Note that some utilities (21-UTIL) are exported, but not biomass electricity (BIOM) directly. The annual maps for each scenario are not provided as they generally suggest the same spatial pattern as the baseline, only at slightly elevated levels. However, they are all available within the Supplemental Materials.

	Changes in 2025 FPI output by sector from the baseline estimate				
	base	**none**	**reg**	**mod**	**full**
BIOM	*4.30%*	0.21%	0.25%	0.23%	0.22%
SAW	*14.65%*	1.70%	3.24%	4.48%	5.63%
STRUC	*5.03%*	0.30%	2.30%	4.19%	5.91%
ARCH	*4.42%*	0.14%	1.44%	2.70%	3.83%
FMWP	*4.82%*	0.80%	2.59%	4.21%	5.68%
PULP	*5.15%*	1.45%	3.43%	5.12%	6.64%
PAPE	*7.03%*	9.35%	9.58%	8.28%	7.04%
FURN	*4.37%*	-0.10%	2.22%	4.46%	6.48%

Table 34. The additional percentage change in final FPI sector output from the 2025 baseline. Base represents the final in 2025 change from 2016 in the baseline scenario. Base represents the final change from 2016 in the baseline scenario. The other columns represent the additional change from the corresponding year in the baseline.

	Changes in 2025 FPI prices from the baseline estimate				
	base	**none**	**reg**	**mod**	**full**
BIOM	*22.43%*	0.21%	0.24%	0.23%	0.21%
SAW	*11.29%*	1.67%	3.28%	4.67%	5.87%
STRUC	*21.48%*	0.30%	2.30%	4.21%	5.93%
ARCH	*22.05%*	0.14%	1.44%	2.70%	3.84%
FMWP	*21.76%*	0.80%	2.59%	4.21%	5.68%
PULP	*21.35%*	1.46%	3.44%	5.12%	6.65%
PAPE	*19.32%*	9.22%	9.44%	8.16%	6.94%
FURN	*22.35%*	-0.10%	2.22%	4.46%	6.48%

Table 35. The additional percentage change in final FPI sector prices from the 2025 baseline. Base represents the final in 2025 change from 2016 in the baseline scenario. Base represents the change from 2016 in the baseline scenario. The other columns represent the additional change from the corresponding year in the baseline.

CHAPTER 6

CONCLUSIONS

Overall, the DR.SAGE model has some real advantages. While somewhat simplistic, it provides a very complete view of Maine's economy. The model provides detailed information about Maine's forest product industry. This includes specific harvest locations, prices, and quantities. In this way, the DR.SAGE model provides similar information to a partial equilibrium model. At the same time, the model provides more general information about the forest product sectors and other productive sectors, institutions, and factors in Maine. Each of these could be expanded to the detail level of stands with more time and data.

Adding more supply and demand centers for a higher level of detail will take slightly longer to solve, but otherwise offers no restrictions. For now, these pieces of Maine's economy are analyzed at a county level with the model supplying current dollar outputs and relative prices for each piece on an annual basis. This allows for the DR.SAGE model to be used in a GE capacity, examining impacts across all sectors, in all areas. It could also be used to assess the impacts of changes in other sectors besides those that are FPI sectors. While not currently used in this capacity, the mechanism is the same as for implementing a forest industry related shock. The primary difference in these two groups is the level of detail supplied to the model. The DR.SAGE model could be broadened by adding more information about other sectors to more thoroughly examine them instead or in addition.

The DR.SAGE model functions efficiently, but could still benefit from some technical improvements. Currently, nearly all the results were compiled outside of the model after the runs. For now, this provides more flexibility in the presentation of results. Ultimately, the next step for improving the DR.SAGE model is making it more user-friendly by automating these compilation procedures into the model script. Similarly, an improvement in the model's solution time will make it a more comfortable and useful tool for others. The model executes quickly enough to run new scenarios in a few hours; however, I believe the DR.SAGE model can be significantly sped up. This could allow faster analyses and larger models. It is also important to simplify the implementation of scenarios, the management of inputs, and the vast amount of outputs.

The DR.SAGE model performs very well with demand driven shocks, easily translating them into the relevant output and price changes. In the FOR/Maine scenarios, after being supplied with annual growth rates, the DR.SAGE model provides a detailed account of the resulting changes in each industry. Being a demand driven model, the DR.SAGE does not effectively handle changes in supply unless they are explicitly paired with a change in price. This was the case with the spruce budworm scenarios. Salvaged wood was forced into the market and treated as a perfect substitute for regularly harvested wood. An important next step for improving this modeling scenario will be to remove the forced market entry and instead implement a differential price mechanism for salvaged wood. After this, my next set of scenarios will enact a carbon tax.

Most importantly, the DR.SAGE model achieves its three objectives. The model endogenously incorporates Maine timber supply and growth, has the specificity to closely examine the forest products industry, and assesses the impact of any shocks across the entire economy. It also has the flexibility to incorporate a wide array of demand driven shocks. I believe that the DR.SAGE modeling framework will be a valuable tool for Maine and has high potential for implementation in other areas and perhaps even for other industries.

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APPENDIX A

Detailed description of IMPLAN aggregation used to generate SAM

SAM Aggregated Sector	IMPLAN Code	Description	Proportion of Output
11-AGFH (11 Agriculture, Fishing and Hunting, non-Forestry)	1	Oilseed farming	0.08%
	2	Grain farming	1.86%
	3	Vegetable and melon farming	12.31%
	4	Fruit farming	5.83%
	5	Tree nut farming	0.00%
	6	Greenhouse, nursery, and floriculture production	11.64%
	7	Tobacco farming	0.00%
	8	Cotton farming	0.00%
	9	Sugarcane and sugar beet farming	0.00%
	10	All other crop farming	4.12%
	11	Beef cattle ranching and farming, including feedlots and dual-purpose ranching and farming	2.41%
	12	Dairy cattle and milk production	11.01%
	13	Poultry and egg production	7.85%
	14	Animal production, except cattle and poultry and eggs	6.11%
	17	Commercial fishing	36.78%
	18	Commercial hunting and trapping	0.00%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
FORE (Forestry, forest products, and timber tract production)	15	Forestry, forest products, and timber tract production	100.00%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
LOG (Commercial logging)	16	Commercial logging	100.00%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
SUPP (Support activities for agriculture and forestry)	19	Support activities for agriculture and forestry	100.00%

SAM Aggregated Sector	IMPLAN Code	Description	Proportion
21-MGOE (21 Mining, Quarrying, and Oil and Gas Extraction)	20	Extraction of natural gas and crude petroleum	18.92%
	21	Extraction of natural gas liquids	0.00%
	22	Coal mining	0.00%
	23	Iron ore mining	0.00%
	24	Gold ore mining	0.00%
	25	Silver ore mining	0.00%
	26	Lead and zinc ore mining	0.00%
	27	Copper ore mining	0.00%
	28	Uranium-radium-vanadium ore mining	0.00%
	29	Other metal ore mining	0.00%
	30	Stone mining and quarrying	34.85%
	31	Sand and gravel mining	36.63%
	32	Other clay, ceramic, refractory minerals mining	0.00%
	33	Potash, soda, and borate mineral mining	0.00%
	34	Phosphate rock mining	0.00%
	35	Other chemical and fertilizer mineral mining	0.00%
	36	Other nonmetallic minerals	3.02%
	37	Drilling oil and gas wells	5.71%
	38	Support activities for oil and gas operations	0.87%
	39	Metal mining services	0.00%
	40	Other nonmetallic minerals services	0.00%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
22-UTIL (22 Utilities, non-Biomass)	41	Electric power generation - Hydroelectric	6.60%
	42	Electric power generation - Fossil fuel	9.11%
	43	Electric power generation - Nuclear	0.00%
	44	Electric power generation - Solar	0.00%
	45	Electric power generation - Wind	13.63%
	46	Electric power generation - Geothermal	0.00%
	48	Electric power generation - All other	1.86%
	49	Electric power transmission and distribution	59.32%
	50	Natural gas distribution	7.43%
	51	Water, sewage and other systems	2.05%

SAM Aggregated Sector	IMPLAN Code	Description	Proportion
BIOM (Biomass)	47	Electric power generation - Biomass	100.00%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
23-CONS (23 Construction)	52	Construction of new health care structures	2.07%
	53	Construction of new manufacturing structures	3.45%
	54	Construction of new power and communication structures	4.87%
	55	Construction of new educational and vocational structures	4.98%
	56	Construction of new highways and streets	5.14%
	57	Construction of new commercial structures, including farm structures	5.59%
	58	Construction of other new nonresidential structures	12.45%
	59	Construction of new single-family residential structures	10.64%
	60	Construction of new multifamily residential structures	2.80%
	61	Construction of other new residential structures	25.79%
	62	Maintenance and repair construction of nonresidential structures	12.61%
	63	Maintenance and repair construction of residential structures	5.35%
	64	Maintenance and repair construction of highways, streets, bridges, and tunnels	4.25%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
31-NDMFG (31 Non-Forest Product Non-Durable Manufacturing)	65	Dog and cat food manufacturing	0.10%
	66	Other animal food manufacturing	3.18%
	67	Flour milling	0.37%
	68	Rice milling	0.00%
	69	Malt manufacturing	0.54%
	70	Wet corn milling	1.43%
	71	Soybean and other oilseed processing	0.00%

	72	Fats and oils refining and blending	0.00%
	73	Breakfast cereal manufacturing	0.00%
	74	Beet sugar manufacturing	0.00%
	75	Sugar cane mills and refining	0.00%
	76	Nonchocolate confectionery manufacturing	1.00%
	77	Chocolate and confectionery manufacturing from cacao beans	0.00%
	78	Confectionery manufacturing from purchased chocolate	1.23%
	79	Frozen fruits, juices and vegetables manufacturing	7.03%
	80	Frozen specialties manufacturing	1.61%
	81	Canned fruits and vegetables manufacturing	3.40%
	82	Canned specialties	2.00%
	83	Dehydrated food products manufacturing	0.10%
	84	Fluid milk manufacturing	6.81%
	85	Creamery butter manufacturing	0.49%
	86	Cheese manufacturing	0.43%
	87	Dry, condensed, and evaporated dairy product manufacturing	0.00%
	88	Ice cream and frozen dessert manufacturing	0.81%
	89	Animal, except poultry, slaughtering	1.82%
	90	Meat processed from carcasses	3.58%
	91	Rendering and meat byproduct processing	0.00%
	92	Poultry processing	0.08%
	93	Seafood product preparation and packaging	7.30%
	94	Bread and bakery product, except frozen, manufacturing	5.34%
	95	Frozen cakes and other pastries manufacturing	0.99%
	96	Cookie and cracker manufacturing	0.08%
	97	Dry pasta, mixes, and dough manufacturing	0.84%
	98	Tortilla manufacturing	0.01%
	99	Roasted nuts and peanut butter manufacturing	0.00%

	100	Other snack food manufacturing	0.44%
	101	Coffee and tea manufacturing	0.23%
	102	Flavoring syrup and concentrate manufacturing	0.35%
	103	Mayonnaise, dressing, and sauce manufacturing	0.46%
	104	Spice and extract manufacturing	0.36%
	105	All other food manufacturing	3.58%
	106	Bottled and canned soft drinks & water	13.38%
	107	Manufactured ice	0.10%
	108	Breweries	7.68%
	109	Wineries	0.43%
	110	Distilleries	3.39%
	111	Tobacco product manufacturing	0.00%
	112	Fiber, yarn, and thread mills	0.52%
	113	Broadwoven fabric mills	3.34%
	114	Narrow fabric mills and schiffli machine embroidery	0.27%
	115	Nonwoven fabric mills	1.23%
	116	Knit fabric mills	0.48%
	117	Textile and fabric finishing mills	0.28%
	118	Fabric coating mills	0.48%
	119	Carpet and rug mills	0.76%
	120	Curtain and linen mills	0.19%
	121	Textile bag and canvas mills	0.75%
	122	Rope, cordage, twine, tire cord and tire fabric mills	1.39%
	123	Other textile product mills	0.45%
	124	Hosiery and sock mills	0.00%
	125	Other apparel knitting mills	0.00%
	126	Cut and sew apparel contractors	0.02%
	127	Mens and boys cut and sew apparel manufacturing	0.10%
	128	Womens and girls cut and sew apparel manufacturing	0.38%
	129	Other cut and sew apparel manufacturing	0.39%
	130	Apparel accessories and other apparel manufacturing	0.25%
	131	Leather and hide tanning and finishing	1.90%
	132	Footwear manufacturing	5.30%

	133	Other leather and allied product manufacturing	0.58%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
SAW (Sawmills)	134	Sawmills	90.21%
	135	Wood preservation	6.01%
	140	Cut stock, resawing lumber, and planing	3.79%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
STRUC (Structural Wood Product Manufacturing)	136	Veneer and plywood manufacturing	17.29%
	137	Engineered wood member and truss manufacturing	18.81%
	138	Reconstituted wood product manufacturing	63.90%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
ARCH (Architectural Millwork)	139	Wood windows and door manufacturing	42.00%
	141	Other millwork, including flooring	26.78%
	374	Custom architectural woodwork and millwork	31.22%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
FMWP (Final Product and Miscellaneous Manufacturing)	142	Wood container and pallet manufacturing	17.13%
	144	Prefabricated wood building manufacturing	27.64%
	145	All other miscellaneous wood product manufacturing	55.24%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
32-MMFG (32 Non-Forest Product Materials Manufacturing)	143	Manufactured home (mobile home) manufacturing	0.00%
	154	Printing	6.06%
	155	Support activities for printing	0.07%
	156	Petroleum refineries	20.22%
	157	Asphalt paving mixture and block manufacturing	2.55%

	158	Asphalt shingle and coating materials manufacturing	0.00%
	159	Petroleum lubricating oil and grease manufacturing	0.00%
	160	All other petroleum and coal products manufacturing	0.00%
	161	Petrochemical manufacturing	4.08%
	162	Industrial gas manufacturing	0.42%
	163	Synthetic dye and pigment manufacturing	0.03%
	164	Other basic inorganic chemical manufacturing	1.46%
	165	Other basic organic chemical manufacturing	0.40%
	166	Plastics material and resin manufacturing	1.36%
	167	Synthetic rubber manufacturing	1.07%
	168	Artificial and synthetic fibers and filaments manufacturing	0.00%
	169	Nitrogenous fertilizer manufacturing	1.12%
	170	Phosphatic fertilizer manufacturing	0.00%
	171	Fertilizer mixing	0.36%
	172	Pesticide and other agricultural chemical manufacturing	0.00%
	173	Medicinal and botanical manufacturing	2.74%
	174	Pharmaceutical preparation manufacturing	23.93%
	175	In-vitro diagnostic substance manufacturing	2.16%
	176	Biological product (except diagnostic) manufacturing	1.90%
	177	Paint and coating manufacturing	0.50%
	178	Adhesive manufacturing	0.00%
	179	Soap and other detergent manufacturing	2.05%
	180	Polish and other sanitation good manufacturing	0.45%
	181	Surface active agent manufacturing	0.13%
	182	Toilet preparation manufacturing	1.48%
	183	Printing ink manufacturing	0.02%
	184	Explosives manufacturing	0.00%
	185	Custom compounding of purchased resins	0.00%

	186	Photographic film and chemical manufacturing	0.00%
	187	Other miscellaneous chemical product manufacturing	0.39%
	188	Plastics packaging materials and unlaminated film and sheet manufacturing	1.87%
	189	Unlaminated plastics profile shape manufacturing	0.00%
	190	Plastics pipe and pipe fitting manufacturing	1.51%
	191	Laminated plastics plate, sheet (except packaging), and shape manufacturing	3.39%
	192	Polystyrene foam product manufacturing	0.00%
	193	Urethane and other foam product (except polystyrene) manufacturing	2.01%
	194	Plastics bottle manufacturing	0.56%
	195	Other plastics product manufacturing	6.86%
	196	Tire manufacturing	0.33%
	197	Rubber and plastics hoses and belting manufacturing	0.00%
	198	Other rubber product manufacturing	0.25%
	199	Pottery, ceramics, and plumbing fixture manufacturing	0.36%
	200	Brick, tile, and other structural clay product manufacturing	0.29%
	201	Flat glass manufacturing	0.00%
	202	Other pressed and blown glass and glassware manufacturing	0.00%
	203	Glass container manufacturing	0.00%
	204	Glass product manufacturing made of purchased glass	0.96%
	205	Cement manufacturing	0.79%
	206	Ready-mix concrete manufacturing	2.14%
	207	Concrete block and brick manufacturing	0.79%
	208	Concrete pipe manufacturing	0.00%
	209	Other concrete product manufacturing	1.21%
	210	Lime manufacturing	0.00%
	211	Gypsum product manufacturing	0.36%
	212	Abrasive product manufacturing	0.00%
	213	Cut stone and stone product manufacturing	0.84%

	214	Ground or treated mineral and earth manufacturing	0.19%
	215	Mineral wool manufacturing	0.10%
	216	Miscellaneous nonmetallic mineral products manufacturing	0.26%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
PULP (Pulp Mills)	146	Pulp mills	100.00%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
PAPE (Paper Manufacturing)	147	Paper mills	81.12%
	148	Paperboard mills	0.00%
	149	Paperboard container manufacturing	4.39%
	150	Paper bag and coated and treated paper manufacturing	0.45%
	151	Stationery product manufacturing	0.41%
	152	Sanitary paper product manufacturing	8.61%
	153	All other converted paper product manufacturing	5.03%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
33-DMFG (33 Non-Forest Product Durable Manufacturing)	217	Iron and steel mills and ferroalloy manufacturing	0.00%
	218	Iron, steel pipe and tube manufacturing from purchased steel	0.00%
	219	Rolled steel shape manufacturing	0.00%
	220	Steel wire drawing	0.01%
	221	Alumina refining and primary aluminum production	0.00%
	222	Secondary smelting and alloying of aluminum	0.00%
	223	Aluminum sheet, plate, and foil manufacturing	0.00%
	224	Other aluminum rolling, drawing and extruding	0.00%
	225	Nonferrous metal (exc aluminum) smelting and refining	0.00%
	226	Copper rolling, drawing, extruding and alloying	0.00%

	227	Nonferrous metal, except copper and aluminum, shaping	1.27%
	228	Secondary processing of other nonferrous metals	0.36%
	229	Ferrous metal foundries	0.23%
	230	Nonferrous metal foundries	0.03%
	231	Iron and steel forging	0.00%
	232	Nonferrous forging	0.00%
	233	Custom roll forming	0.00%
	234	Crown and closure manufacturing and metal stamping	0.15%
	235	Cutlery, utensil, pot, and pan manufacturing	0.09%
	236	Handtool manufacturing	0.67%
	237	Prefabricated metal buildings and components manufacturing	0.43%
	238	Fabricated structural metal manufacturing	2.75%
	239	Plate work manufacturing	0.69%
	240	Metal window and door manufacturing	0.50%
	241	Sheet metal work manufacturing	1.01%
	242	Ornamental and architectural metal work manufacturing	0.15%
	243	Power boiler and heat exchanger manufacturing	0.00%
	244	Metal tank (heavy gauge) manufacturing	0.15%
	245	Metal cans manufacturing	0.00%
	246	Metal barrels, drums and pails manufacturing	0.00%
	247	Hardware manufacturing	0.09%
	248	Spring and wire product manufacturing	0.96%
	249	Machine shops	4.54%
	250	Turned product and screw, nut, and bolt manufacturing	2.00%
	251	Metal heat treating	0.24%
	252	Metal coating and nonprecious engraving	0.65%
	253	Electroplating, anodizing, and coloring metal	0.33%
	254	Valve and fittings, other than plumbing, manufacturing	0.16%

	255	Plumbing fixture fitting and trim manufacturing	0.00%
	256	Ball and roller bearing manufacturing	0.00%
	257	Small arms ammunition manufacturing	0.02%
	258	Ammunition, except for small arms, manufacturing	0.02%
	259	Small arms, ordnance, and accessories manufacturing	2.50%
	260	Fabricated pipe and pipe fitting manufacturing	0.35%
	261	Other fabricated metal manufacturing	0.55%
	262	Farm machinery and equipment manufacturing	0.11%
	263	Lawn and garden equipment manufacturing	0.11%
	264	Construction machinery manufacturing	3.32%
	265	Mining machinery and equipment manufacturing	0.00%
	266	Oil and gas field machinery and equipment manufacturing	0.00%
	267	Food product machinery manufacturing	0.08%
	268	Semiconductor machinery manufacturing	0.00%
	270	Printing machinery and equipment manufacturing	0.00%
	271	All other industrial machinery manufacturing	0.29%
	272	Optical instrument and lens manufacturing	0.19%
	273	Photographic and photocopying equipment manufacturing	0.00%
	274	Other commercial service industry machinery manufacturing	0.23%
	275	Air purification and ventilation equipment manufacturing	0.00%
	276	Heating equipment (except warm air furnaces) manufacturing	0.34%
	277	Air conditioning, refrigeration, and warm air heating equipment manufacturing	0.39%
	278	Industrial mold manufacturing	0.08%
	279	Special tool, die, jig, and fixture manufacturing	0.48%

	280	Cutting tool and machine tool accessory manufacturing	0.56%
	281	Machine tool manufacturing	0.00%
	282	Rolling mill and other metalworking machinery manufacturing	0.93%
	283	Turbine and turbine generator set units manufacturing	2.84%
	284	Speed changer, industrial high-speed drive, and gear manufacturing	0.16%
	285	Mechanical power transmission equipment manufacturing	0.00%
	286	Other engine equipment manufacturing	0.00%
	287	Pump and pumping equipment manufacturing	0.12%
	288	Air and gas compressor manufacturing	0.00%
	289	Measuring and dispensing pump manufacturing	0.19%
	290	Elevator and moving stairway manufacturing	0.00%
	291	Conveyor and conveying equipment manufacturing	0.36%
	292	Overhead cranes, hoists, and monorail systems manufacturing	0.14%
	293	Industrial truck, trailer, and stacker manufacturing	0.11%
	294	Power-driven handtool manufacturing	0.00%
	295	Welding and soldering equipment manufacturing	0.04%
	296	Packaging machinery manufacturing	0.35%
	297	Industrial process furnace and oven manufacturing	0.77%
	298	Fluid power cylinder and actuator manufacturing	0.04%
	299	Fluid power pump and motor manufacturing	0.00%
	300	Scales, balances, and miscellaneous general purpose machinery manufacturing	0.33%
	301	Electronic computer manufacturing	0.00%
	302	Computer storage device manufacturing	0.00%
	303	Computer terminals and other computer peripheral equipment manufacturing	0.00%

	304	Telephone apparatus manufacturing	0.00%
	305	Broadcast and wireless communications equipment manufacturing	0.36%
	306	Other communications equipment manufacturing	1.10%
	307	Audio and video equipment manufacturing	0.03%
	308	Bare printed circuit board manufacturing	0.00%
	309	Semiconductor and related device manufacturing	7.14%
	310	Capacitor, resistor, coil, transformer, and other inductor manufacturing	0.90%
	311	Electronic connector manufacturing	0.28%
	312	Printed circuit assembly (electronic assembly) manufacturing	0.83%
	313	Other electronic component manufacturing	0.30%
	314	Electromedical and electrotherapeutic apparatus manufacturing	0.23%
	315	Search, detection, and navigation instruments manufacturing	0.00%
	316	Automatic environmental control manufacturing	0.04%
	317	Industrial process variable instruments manufacturing	0.09%
	318	Totalizing fluid meter and counting device manufacturing	0.00%
	319	Electricity and signal testing instruments manufacturing	0.02%
	320	Analytical laboratory instrument manufacturing	1.17%
	321	Irradiation apparatus manufacturing	0.00%
	322	Watch, clock, and other measuring and controlling device manufacturing	0.22%
	323	Blank magnetic and optical recording media manufacturing	0.00%
	324	Software and other prerecorded and record reproducing	0.01%
	325	Electric lamp bulb and part manufacturing	0.06%
	326	Lighting fixture manufacturing	0.02%
	327	Small electrical appliance manufacturing	0.00%

	328	Household cooking appliance manufacturing	0.00%
	329	Household refrigerator and home freezer manufacturing	0.00%
	330	Household laundry equipment manufacturing	0.00%
	331	Other major household appliance manufacturing	0.00%
	332	Power, distribution, and specialty transformer manufacturing	0.00%
	333	Motor and generator manufacturing	0.12%
	334	Switchgear and switchboard apparatus manufacturing	1.16%
	335	Relay and industrial control manufacturing	0.52%
	336	Storage battery manufacturing	0.00%
	337	Primary battery manufacturing	0.00%
	338	Fiber optic cable manufacturing	0.00%
	339	Other communication and energy wire manufacturing	0.10%
	340	Wiring device manufacturing	0.45%
	341	Carbon and graphite product manufacturing	0.01%
	342	All other miscellaneous electrical equipment and component manufacturing	0.01%
	343	Automobile manufacturing	0.04%
	344	Light truck and utility vehicle manufacturing	0.00%
	345	Heavy duty truck manufacturing	2.59%
	346	Motor vehicle body manufacturing	0.18%
	347	Truck trailer manufacturing	0.03%
	348	Motor home manufacturing	0.00%
	349	Travel trailer and camper manufacturing	0.92%
	350	Motor vehicle gasoline engine and engine parts manufacturing	0.09%
	351	Motor vehicle electrical and electronic equipment manufacturing	0.08%
	352	Motor vehicle steering, suspension component (except spring), and brake systems manufacturing	0.74%

	353	Motor vehicle transmission and power train parts manufacturing	0.00%
	354	Motor vehicle seating and interior trim manufacturing	0.00%
	355	Motor vehicle metal stamping	0.00%
	356	Other motor vehicle parts manufacturing	0.12%
	357	Aircraft manufacturing	0.39%
	358	Aircraft engine and engine parts manufacturing	8.56%
	359	Other aircraft parts and auxiliary equipment manufacturing	0.33%
	360	Guided missile and space vehicle manufacturing	0.00%
	361	Propulsion units and parts for space vehicles and guided missiles manufacturing	0.80%
	362	Railroad rolling stock manufacturing	0.00%
	363	Ship building and repairing	21.60%
	364	Boat building	6.27%
	365	Motorcycle, bicycle, and parts manufacturing	0.25%
	366	Military armored vehicle, tank, and tank component manufacturing	0.00%
	367	All other transportation equipment manufacturing	0.00%
	372	Institutional furniture manufacturing	0.72%
	377	Mattress manufacturing	0.05%
	378	Blind and shade manufacturing	0.00%
	379	Surgical and medical instrument manufacturing	0.14%
	380	Surgical appliance and supplies manufacturing	3.43%
	381	Dental equipment and supplies manufacturing	0.03%
	382	Ophthalmic goods manufacturing	0.07%
	383	Dental laboratories	0.14%
	384	Jewelry and silverware manufacturing	0.58%
	385	Sporting and athletic goods manufacturing	0.38%
	386	Doll, toy, and game manufacturing	0.33%
	387	Office supplies (except paper) manufacturing	0.09%

	388	Sign manufacturing	0.66%
	389	Gasket, packing, and sealing device manufacturing	0.11%
	390	Musical instrument manufacturing	0.12%
	391	Fasteners, buttons, needles, and pins manufacturing	0.00%
	392	Broom, brush, and mop manufacturing	0.18%
	393	Burial casket manufacturing	0.00%
	394	All other miscellaneous manufacturing	1.34%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
MACH (FPI Related Machinery Manufacturing)	269	Sawmill, woodworking, and paper machinery	100.00%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
FURN (Wood Furnitute Manufacturing)	368	Wood kitchen cabinet and countertop manufacturing	28.77%
	369	Upholstered household furniture manufacturing	2.16%
	370	Nonupholstered wood household furniture manufacturing	33.36%
	371	Other household nonupholstered furniture manufacturing	0.00%
	373	Wood office furniture manufacturing	1.20%
	375	Office furniture, except wood, manufacturing	1.24%
	376	Showcase, partition, shelving, and locker manufacturing	33.28%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
42-WHOL (42 Wholesale Trade)	395	Wholesale trade	100.00%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
44-RTAL (44-45 Retail Trade)	396	Retail - Motor vehicle and parts dealers	11.35%
	397	Retail - Furniture and home furnishings stores	2.57%
	398	Retail - Electronics and appliance stores	1.83%
	399	Retail - Building material and garden equipment and supplies stores	10.84%

	400	Retail - Food and beverage stores	15.25%
	401	Retail - Health and personal care stores	5.80%
	402	Retail - Gasoline stores	5.90%
	403	Retail - Clothing and clothing accessories stores	6.00%
	404	Retail - Sporting goods, hobby, musical instrument and book stores	2.92%
	405	Retail - General merchandise stores	12.24%
	406	Retail - Miscellaneous store retailers	5.04%
	407	Retail - Nonstore retailers	20.28%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
48-TRWH (48-49 Transportation and Warehousing)	408	Air transportation	3.41%
	409	Rail transportation	5.26%
	410	Water transportation	3.55%
	411	Truck transportation	39.07%
	412	Transit and ground passenger transportation	5.12%
	413	Pipeline transportation	1.20%
	414	Scenic and sightseeing transportation and support activities for transportation	9.18%
	415	Couriers and messengers	9.63%
	416	Warehousing and storage	13.92%
	518	Postal service	9.66%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
51-INFO (51 Information)	417	Newspaper publishers	5.14%
	418	Periodical publishers	3.66%
	419	Book publishers	4.39%
	420	Directory, mailing list, and other publishers	0.48%
	421	Greeting card publishing	0.46%
	422	Software publishers	2.79%
	423	Motion picture and video industries	3.68%
	424	Sound recording industries	0.52%
	425	Radio and television broadcasting	6.67%
	426	Cable and other subscription programming	0.81%
	427	Wired telecommunications carriers	22.63%

	428	Wireless telecommunications carriers (except satellite)	25.79%
	429	Satellite, telecommunications resellers, and all other telecommunications	0.64%
	430	Data processing, hosting, and related services	6.91%
	431	News syndicates, libraries, archives and all other information services	13.79%
	432	Internet publishing and broadcasting and web search portals	1.63%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
52-FINA (52 Finance and Insurance)	433	Monetary authorities and depository credit intermediation	20.69%
	434	Nondepository credit intermediation and related activities	8.50%
	435	Securities and commodity contracts intermediation and brokerage	2.77%
	436	Other financial investment activities	10.63%
	437	Insurance carriers	36.57%
	438	Insurance agencies, brokerages, and related activities	14.98%
	439	Funds, trusts, and other financial vehicles	5.86%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
53a-REAL (53a Real Estate)	440	Real estate	46.69%
	441	Owner-occupied dwellings	53.31%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
53b-RENT (53b Rental and Leasing)	442	Automotive equipment rental and leasing	31.63%
	443	General and consumer goods rental except video tapes and discs	8.57%
	444	Video tape and disc rental	2.06%
	445	Commercial and industrial machinery and equipment rental and leasing	19.35%
	446	Lessors of nonfinancial intangible assets	38.39%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**

54-PROF (54 Professional, Scientific, and Technical Services)	447	Legal services	12.82%
	448	Accounting, tax preparation, bookkeeping, and payroll services	6.54%
	449	Architectural, engineering, and related services	14.41%
	450	Specialized design services	1.45%
	451	Custom computer programming services	11.49%
	452	Computer systems design services	3.50%
	453	Other computer related services, including facilities management	2.12%
	454	Management consulting services	6.73%
	455	Environmental and other technical consulting services	2.07%
	456	Scientific research and development services	24.21%
	457	Advertising, public relations, and related services	6.82%
	458	Photographic services	0.91%
	459	Veterinary services	3.05%
	460	Marketing research and all other miscellaneous professional, scientific, and technical services	3.89%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
55-MGMT (55-56 Management of Companies and Administrative and Support and Waste Management and Remediation Services)	461	Management of companies and enterprises	38.62%
	462	Office administrative services	7.37%
	463	Facilities support services	1.56%
	464	Employment services	12.36%
	465	Business support services	8.59%
	466	Travel arrangement and reservation services	2.90%
	467	Investigation and security services	1.95%
	468	Services to buildings	6.32%
	469	Landscape and horticultural services	8.36%

	470	Other support services	3.01%
	471	Waste management and remediation services	8.98%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
61-EDUC (61 Educational Services)	472	Elementary and secondary schools	20.65%
	473	Junior colleges, colleges, universities, and professional schools	59.31%
	474	Other educational services	20.04%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
62-HEAL (62 Health Care and Social Assistance)	475	Offices of physicians	13.57%
	476	Offices of dentists	4.84%
	477	Offices of other health practitioners	5.18%
	478	Outpatient care centers	4.28%
	479	Medical and diagnostic laboratories	1.04%
	480	Home health care services	1.88%
	481	Other ambulatory health care services	1.33%
	482	Hospitals	46.54%
	483	Nursing and community care facilities	9.36%
	484	Residential mental retardation, mental health, substance abuse and other facilities	3.04%
	485	Individual and family services	4.88%
	486	Community food, housing, and other relief services, including rehabilitation services	1.63%
	487	Child day care services	2.43%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
71-RECR (71 Arts, Entertainment, and Recreation)	488	Performing arts companies	8.42%
	489	Commercial Sports Except Racing	3.75%
	490	Racing and Track Operation	0.54%
	491	Promoters of performing arts and sports and agents for public figures	8.22%
	492	Independent artists, writers, and performers	12.60%

	493	Museums, historical sites, zoos, and parks	3.51%
	494	Amusement parks and arcades	1.28%
	495	Gambling industries (except casino hotels)	31.27%
	496	Other amusement and recreation industries	24.52%
	497	Fitness and recreational sports centers	4.64%
	498	Bowling centers	1.25%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
72-TOUR (72 Accommodation and Food Services)	499	Hotels and motels, including casino hotels	17.45%
	500	Other accommodations	2.70%
	501	Full-service restaurants	31.39%
	502	Limited-service restaurants	36.35%
	503	All other food and drinking places	12.10%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
81-OTHR (81 Other Services (except Public Administration))	504	Automotive repair and maintenance, except car washes	26.98%
	505	Car washes	1.76%
	506	Electronic and precision equipment repair and maintenance	4.27%
	507	Commercial and industrial machinery and equipment repair and maintenance	7.46%
	508	Personal and household goods repair and maintenance	8.24%
	509	Personal care services	7.51%
	510	Death care services	2.03%
	511	Dry-cleaning and laundry services	1.99%
	512	Other personal services	6.95%
	513	Religious organizations	10.89%
	514	Grantmaking, giving, and social advocacy organizations	10.47%
	515	Business and professional associations	3.88%
	516	Labor and civic organizations	7.57%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**

HOHO (Private Households)	517	Private households	100.00%
SAM Aggregated Sector	**IMPLAN Code**	**Description**	**Proportion**
92-ADMN (92 Public Administration and non-NAICS)	519	Federal electric utilities	0.00%
	520	Other federal government enterprises	0.13%
	521	State government passenger transit	0.00%
	522	State government electric utilities	0.00%
	523	Other state government enterprises	1.48%
	524	Local government passenger transit	0.30%
	525	Local government electric utilities	0.31%
	526	Other local government enterprises	10.65%
	527	* Not an industry (Used and secondhand goods)	0.00%
	528	* Not an industry (Scrap)	0.00%
	529	* Not an industry (Rest of world adjustment)	0.00%
	530	* Not an industry (Noncomparable foreign imports)	0.00%
	531	* Employment and payroll of state govt, non-education	12.19%
	532	* Employment and payroll of state govt, education	5.86%
	533	* Employment and payroll of local govt, non-education	11.94%
	534	* Employment and payroll of local govt, education	29.34%
	535	* Employment and payroll of federal govt, non-military	17.66%
	536	* Employment and payroll of federal govt, military	10.15%

APPENDIX B

Limiting Cases of the CES Production Function: Cobb-Douglas and Leontief Derivations

Given a constant elasticity of substitution style production function (Eq. 8) with $\sum_i a_i = 1$

$$Q = b\left(\sum_i a_i F_i^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$$

the consumer's production function can collapse to either a Cobb-Douglas production function or a Leontief production function depending on the consumer's possibility of substitution.

Let $\frac{\sigma-1}{\sigma} = s$. If substitution is possible, then $\sigma \to 1 \Rightarrow s \to 0$.

$$Q = b\left(\sum_i a_i F_i^s\right)^{\frac{1}{s}} \Rightarrow \ln(Q) = \ln(b) + \frac{1}{s}\ln\,(\sum_i a_i F_i^s)$$

$$\lim_{s\to 0}\ln(Q) = \ln(b) + \lim_{s\to 0}\frac{\ln\,(\sum_i a_i F_i^s)}{s}$$

$$\lim_{s\to 0}\ln\left(\sum_i a_i F_i^s\right) = \lim_{s\to 0}\ln\left(\sum_i a_i F_i^0\right) = \ln\left(\sum_i a_i\right) = \ln(1) = 0$$

$$\lim_{s\to 0} s = 0$$

So, by l'Hospital's rule,

$$\lim_{s\to 0}\frac{\mathrm{f}(\mathrm{s}) = \ln\,(\sum_i a_i F_i^s)}{g(s) = s} = \lim_{s\to 0}\frac{\mathrm{f}'(\mathrm{s}) = {\sum_i a_i F_i^s \ln\,(F_i)}\big/{\sum_i a_i F_i^s}}{g'(s) = 1} = \frac{{\sum_i a_i \ln\,(F_i)}\big/{1}}{1} = \sum_i a_i \ln\,(F_i)$$

$$\lim_{s\to 0}\ln(Q) = \ln(b) + \sum_i a_i \ln\,(F_i)$$

$$\exp(\ln(Q)) = \exp\left(\ln(b) + \sum_i a_i \ln(F_i)\right) \Rightarrow Q = b\prod_i F_i^{a_i}$$

This is the form for a Cobb-Douglas production function.

Again,

$$Q = b\left(\sum_i a_i F_i^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$$

Let $\frac{\sigma-1}{\sigma} = s$. Instead, if substitution is impossible, then $\sigma \to 0 \Rightarrow s \to -\infty$.

$$Q = b\left(\sum_i a_i F_i^s\right)^{\frac{1}{s}} \Rightarrow \ln(Q) = \ln(b) + \frac{1}{s}\ln\left(\sum_i a_i F_i^s\right)$$

$$\lim_{s\to-\infty} \ln(Q) = \ln(b) + \lim_{s\to-\infty} \frac{\ln\left(\sum_i a_i F_i^s\right)}{s}$$

$$\lim_{s\to-\infty} \ln\left(\sum_i a_i F_i^s\right) = \ln\left(\sum_i a_i F_i^{-\infty}\right) = \ln\left(\sum_i a_i \cdot 0\right) = \ln(0) = -\infty$$

$$\lim_{s\to-\infty} s = -\infty$$

So, by l'Hospital's rule,

$$\lim_{s\to-\infty} \frac{\mathrm{f(s)} = \ln\left(\sum_i a_i F_i^s\right)}{g(s) = s} = \lim_{s\to-\infty} \frac{\mathrm{f}'(\mathrm{s}) = {\sum_i a_i F_i^s \ln(F_i)}\Big/{\sum_i a_i F_i^s}}{g'(s) = 1} = \lim_{s\to-\infty} \frac{\sum_i a_i F_i^s \ln(F_i)}{\sum_i a_i F_i^s}$$

WLOG, assume $F_j \le F_i \ \forall\, i \ \Rightarrow \ F_j = \min_i F_i$. Then, dividing both numerator and denominator by F_j^s, we have

$$\lim_{s\to-\infty} \frac{\sum_i a_i \left(\frac{F_i}{F_j}\right)^s \ln(F_i)}{\sum_i a_i \left(\frac{F_i}{F_j}\right)^s}$$

$$\frac{F_i}{F_j} \geq 1 \; \forall \; i \Rightarrow \lim_{s \to -\infty} \left(\frac{F_i}{F_j}\right)^s = 0 \; \forall \; F_i \neq F_j \; or \; 1 \; if \; F_i = F_j$$

$$\lim_{s \to -\infty} \frac{\sum_i a_i \left(\frac{F_i}{F_j}\right)^s \ln\left(F_i\right)}{\sum_i a_i \left(\frac{F_i}{F_j}\right)^s} = \lim_{s \to -\infty} \frac{\sum_{F_i = F_j} a_i \ln\left(F_j\right)}{\sum_{F_i = F_j} a_i} = \ln\left(F_j\right)$$

$$\lim_{s \to -\infty} \ln(Q) = \ln(b) + \lim_{s \to -\infty} \frac{\ln\left(\sum_i a_i F_i^s\right)}{s} = \ln(b) + \ln\left(F_j\right)$$

Therefore,

$$\lim_{s \to -\infty} Q = bF_j = b \min_i F_i$$

This is the form for a Leontief production function.

APPENDIX C

Derivation of Ecological Development Parameters, $\boldsymbol{k_s}$ and $\boldsymbol{C_s}$

Given the following growth specification (Eq. 10)

$$Stock_{pg,s,t} = stock_{pg,s,t-1}[1 + k_s' * \left(1 - \frac{stock_{pg,s,t-1}}{C_s}\right)]$$

We can estimate k_s' and C_s by recognizing that $Stock_{pg,s,t} = stock_{pg,s,t}$ in unharvested stands (Eq. 11). (Note: These stands are still subject to natural mortality and disturbance, however, which means these estimates are for mortality-inclusive growth. This is important to remember if implementing an ecological impact which affects or adjusts mortality.) In such a case,

$$Stock_{pg,s,t} = Stock_{pg,s,t-1} + k_s' Stock_{pg,s,t-1} - \frac{k_s' Stock_{pg,s,t-1}^2}{C_s}$$

Using this relationship, I estimate the following regression model using data from FIA plots which were unharvested between two inventories (for any stand in a given period, even currently harvested stands, if the next period is not marked as harvested, that stand's inventory and five-year growth increment are added as an observation)

$$\Delta Stock_{pg,s,t} = \beta_1 Stock_{pg,s,t-1} + \beta_2 Stock_{pg,s,t-1}^2$$

And we may estimate

$$k_s' = \beta_1 \; and \; C_s = -\frac{\beta_1}{\beta_2}$$

Finally, since FIA plots in Maine are measured on a five year rotation, the growth coefficient k_s actually represents five years of growth. To match the one year periodicity of the model I make the following adjustment

$$k_s = (1 + k_s')^{\frac{model\ period=1}{FIA\ period=5}=0.2} - 1$$

APPENDIX D

Taylor Series Approximations of a Cobb-Douglas Demand Function

The Taylor series expansion is a method of expressing a function as a polynomial sum. The general form is

$$f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!}(x-a)^n$$

We can also use the finite sum $n = 0, \ldots, N$ to generate and N^{th} degree polynomial estimation. Given some Cobb-Douglas demand function for a good

$$Q(p) = \frac{\alpha I}{p}$$

Where I is the demander's income (usually revenue), α is the proportional amount spent on the good, and p is the variable price. If we assume an expected price, p^*, then the Taylor series estimate in the region of that price is

$$Q = \sum_{n=0}^{\infty} \frac{\frac{d^n}{dp^{*n}}(Q = \frac{\alpha I}{p^*})}{n!}(p-p^*)^n$$

$$= \frac{\alpha I}{p^*} - \frac{1\alpha I}{1!\,p^{*2}}(p-p^*) + \frac{2\cdot 1\alpha I}{2!\,p^{*3}}(p-p^*)^2 - \frac{3!\,\alpha I}{3!\,p^{*4}}(p-p^*)^3 + \frac{4!\,\alpha I}{4!\,p^{*5}}(p-p^*)^4 - \cdots$$

$$= \sum_{n=0}^{\infty} \frac{(-1)^n \alpha I}{p^{*n+1}}(p-p^*)^n = \frac{\alpha I}{p^*}\sum_{n=0}^{\infty}(-1)^n \frac{(p-p^*)^n}{p^{*n}} = \frac{\alpha I}{p^*}\sum_{n=0}^{\infty}\left(\frac{-p+p^*}{p^*}\right)^n$$

$$= Q^* \sum_{n=0}^{\infty}\left(1 - \frac{p}{p^*}\right)^n$$

Where Q^* is the quantity associated with the anticipated price, p^*. The zeroth, first, second approximations are, respectively,

$$N = 0 \Rightarrow Q^{(0)} = Q^* \sum_{n=0}^{0} \left(1 - \frac{p}{p^*}\right)^n = Q^*$$

$$N = 1 \Rightarrow Q^{(1)} = Q^* \sum_{n=0}^{1} \left(1 - \frac{p}{p^*}\right)^n = Q^* \left(2 - \frac{p}{p^*}\right)$$

$$N = 2 \Rightarrow Q^{(2)} = Q^* \sum_{n=0}^{2} \left(1 - \frac{p}{p^*}\right)^n = Q^* \left(3 - 3\frac{p}{p^*} + \frac{p^2}{p^{*2}}\right)$$

APPENDIX E: Additional Maps of Forest Product Sector Annual Output and Growth

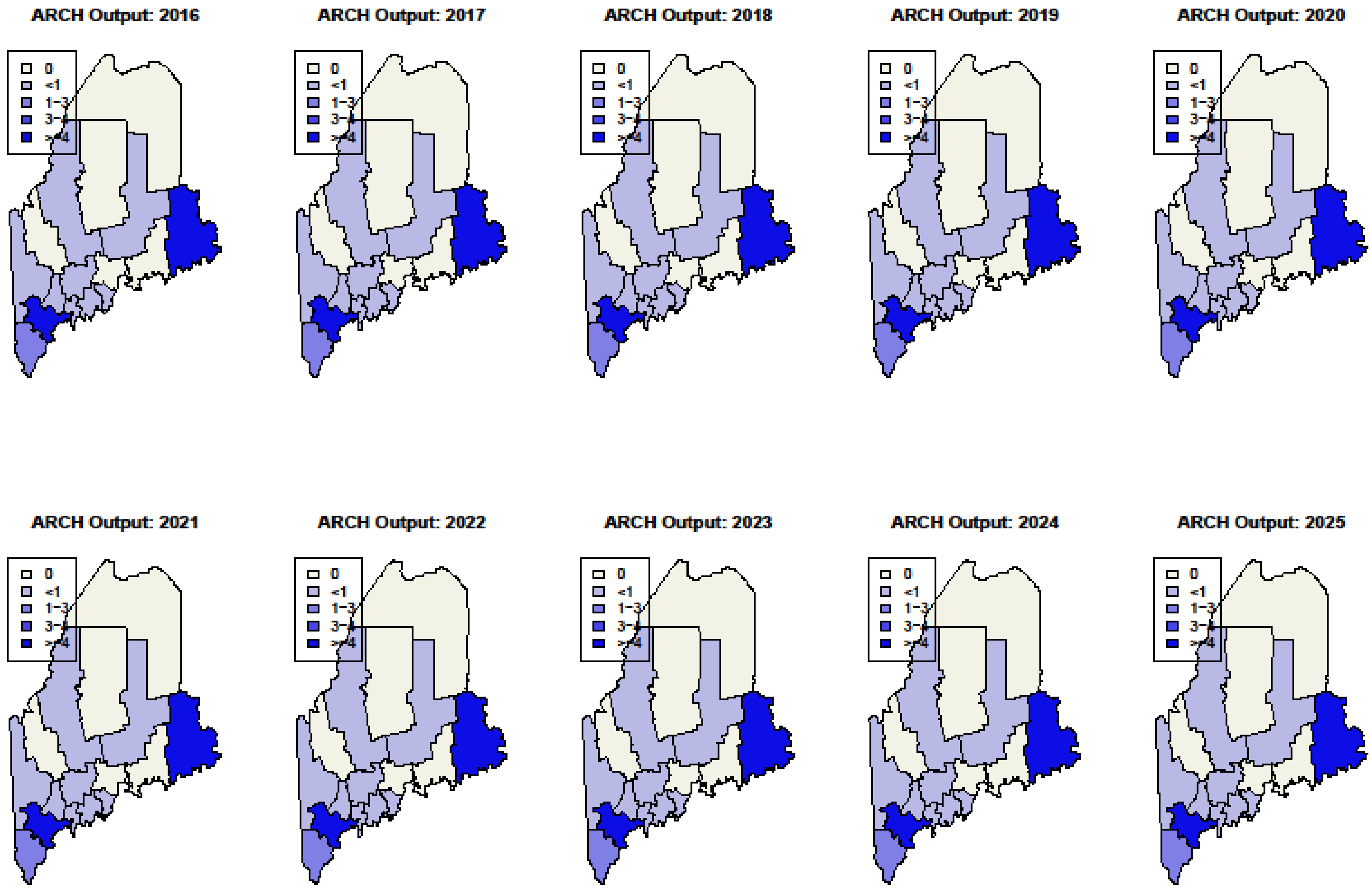

Figure 20. DR.SAGE baseline estimate of the output of architectural goods (ARCH) by county in MMBF.

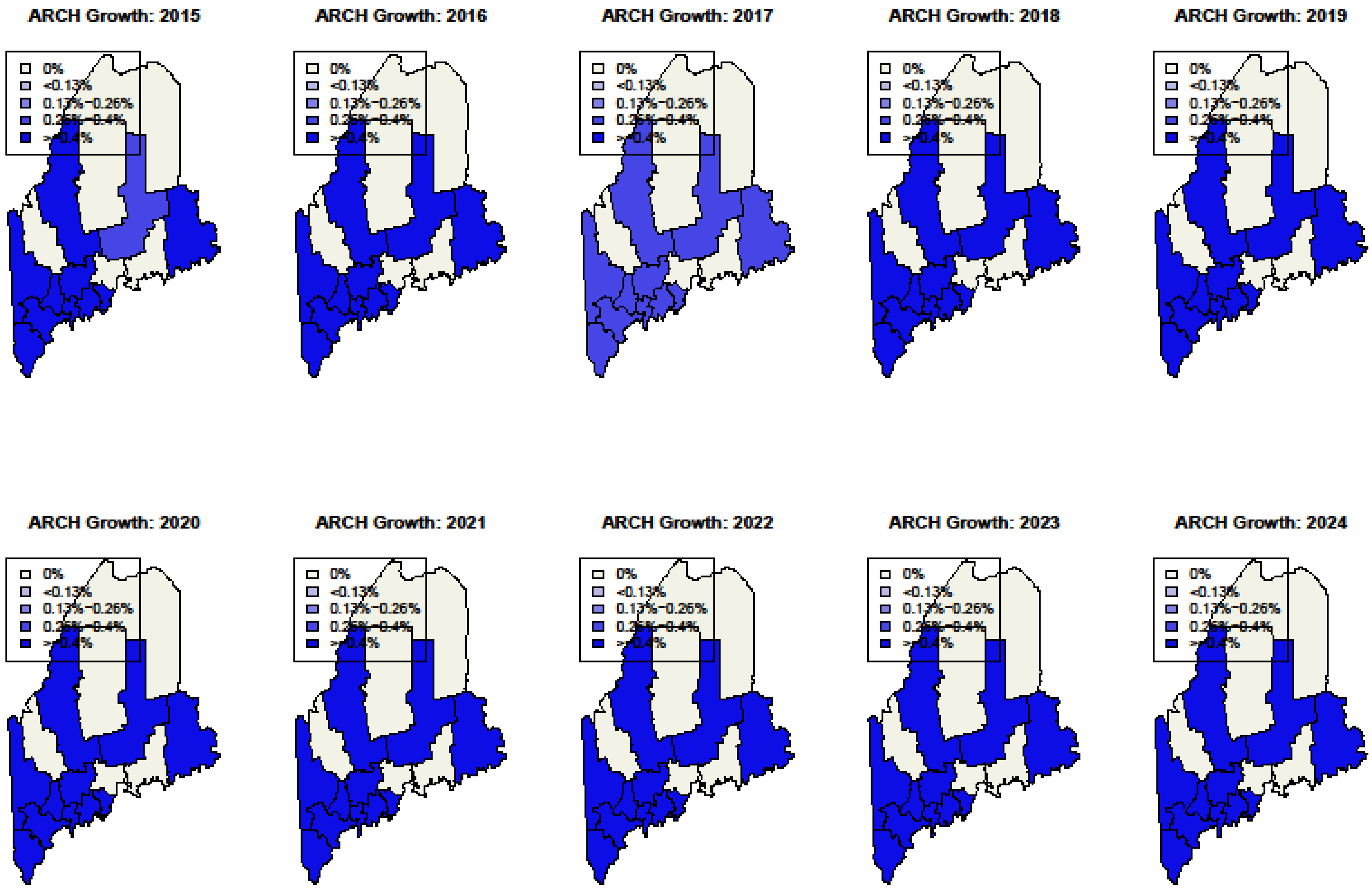

Figure 21. DR.SAGE baseline estimate of the change in architectural goods output (ARCH) by county.

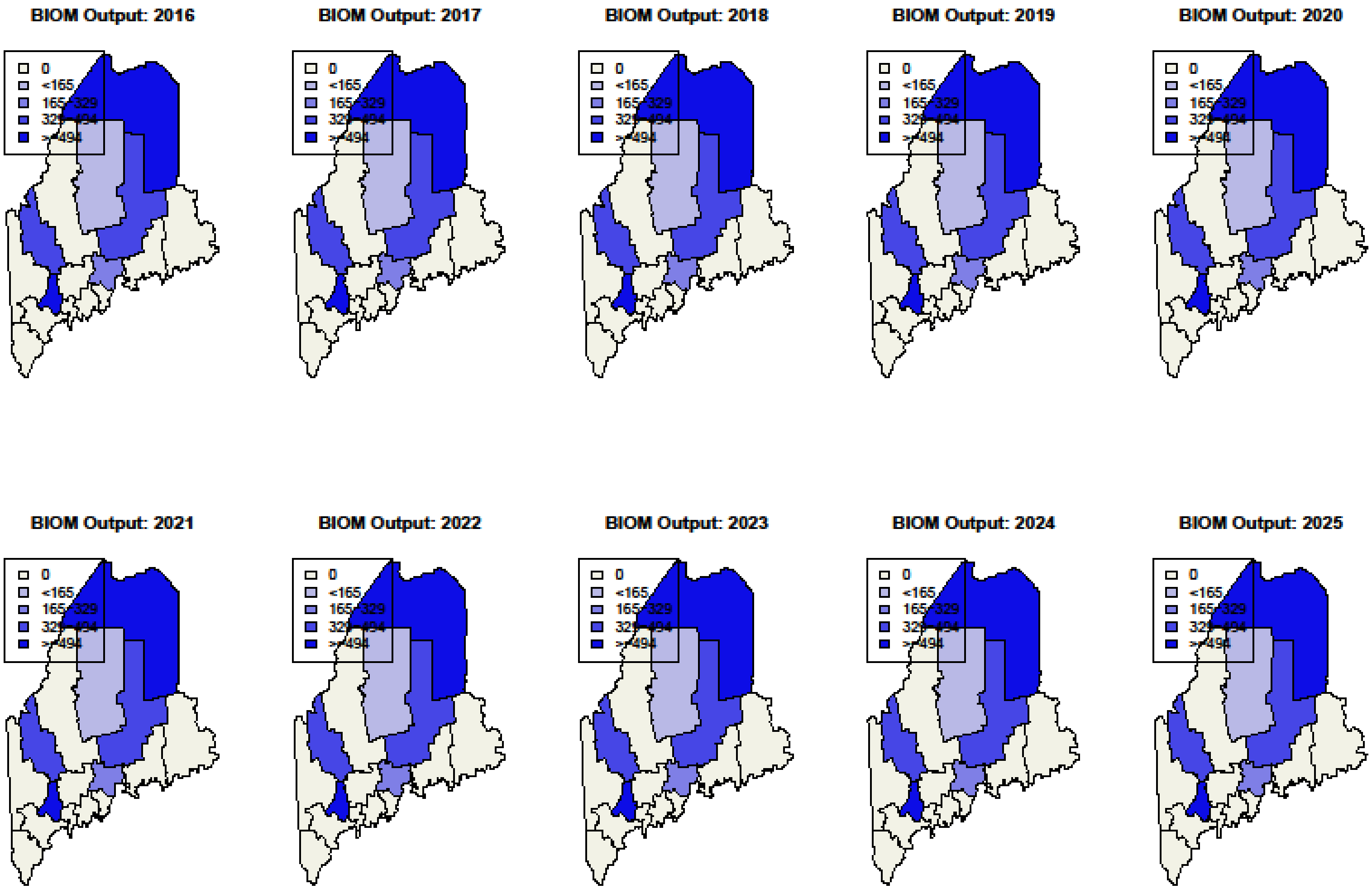

Figure 22. DR.SAGE baseline estimate of the output of biomass electricity (BIOM) by county in MWh.

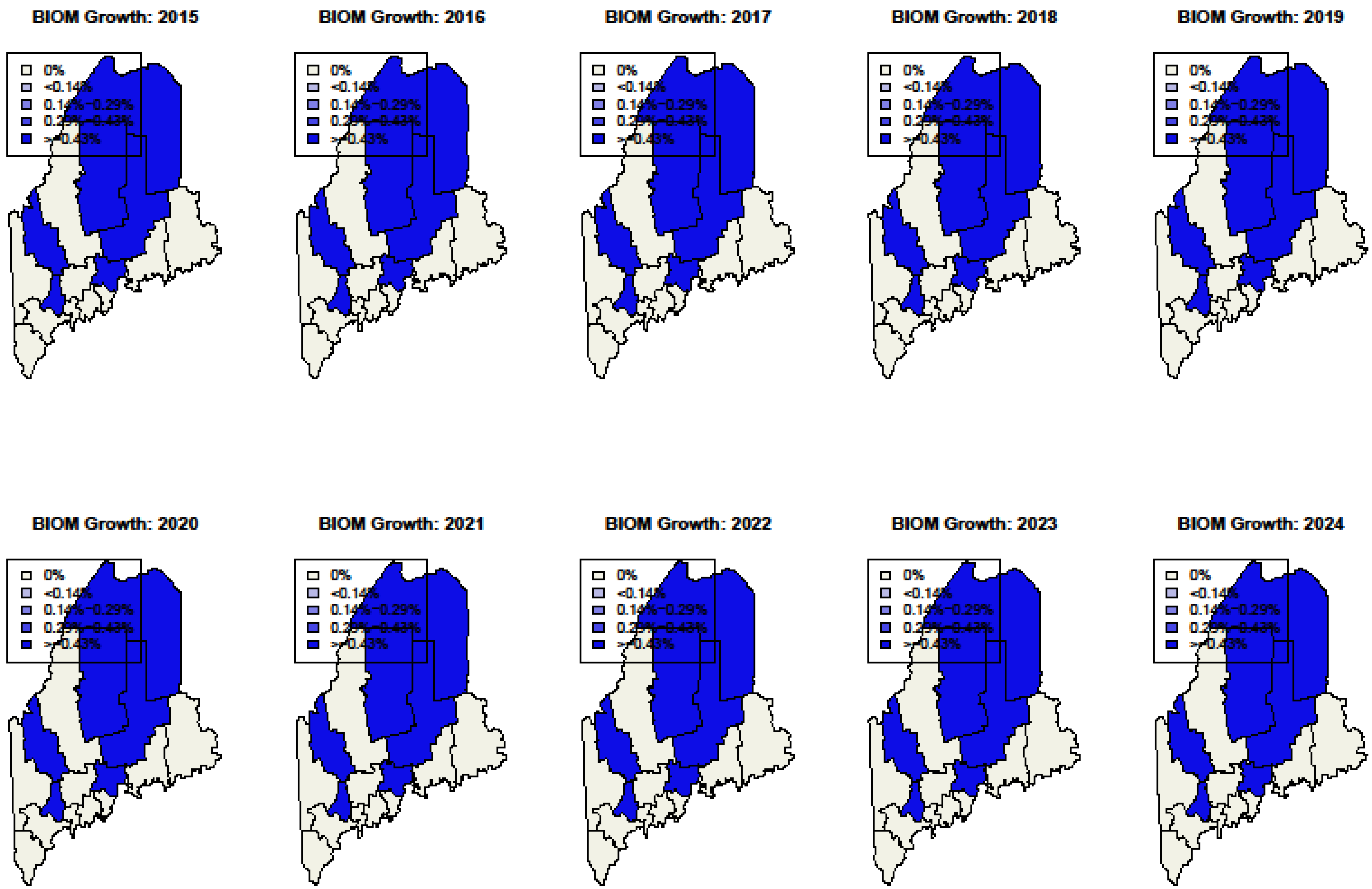

Figure 23. DR.SAGE baseline estimate of the change in biomass electricity output (BIOM) by county.

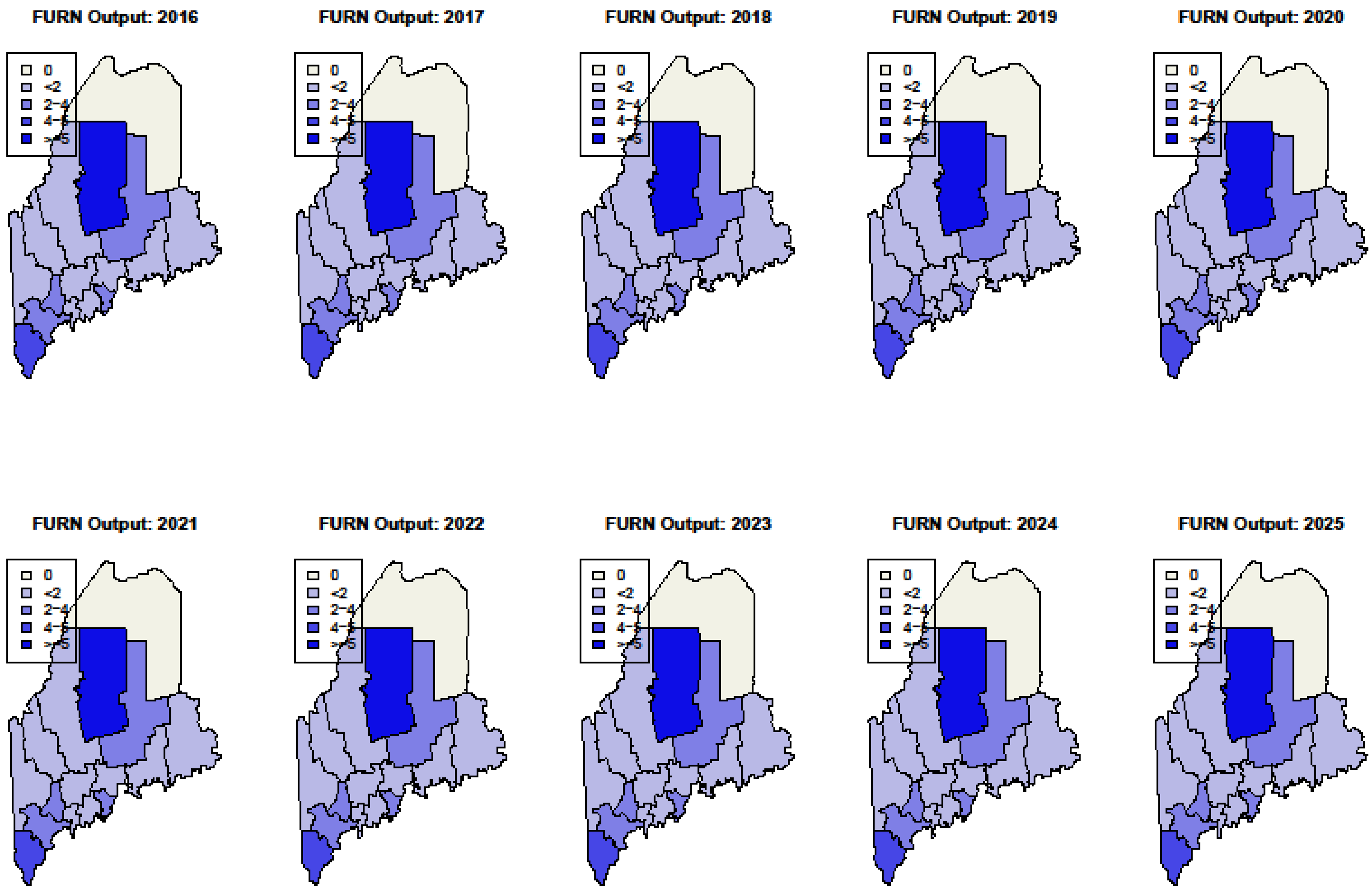

Figure 24. DR.SAGE baseline estimate of the output of furniture products (FURN) by county in thousands of truckloads.

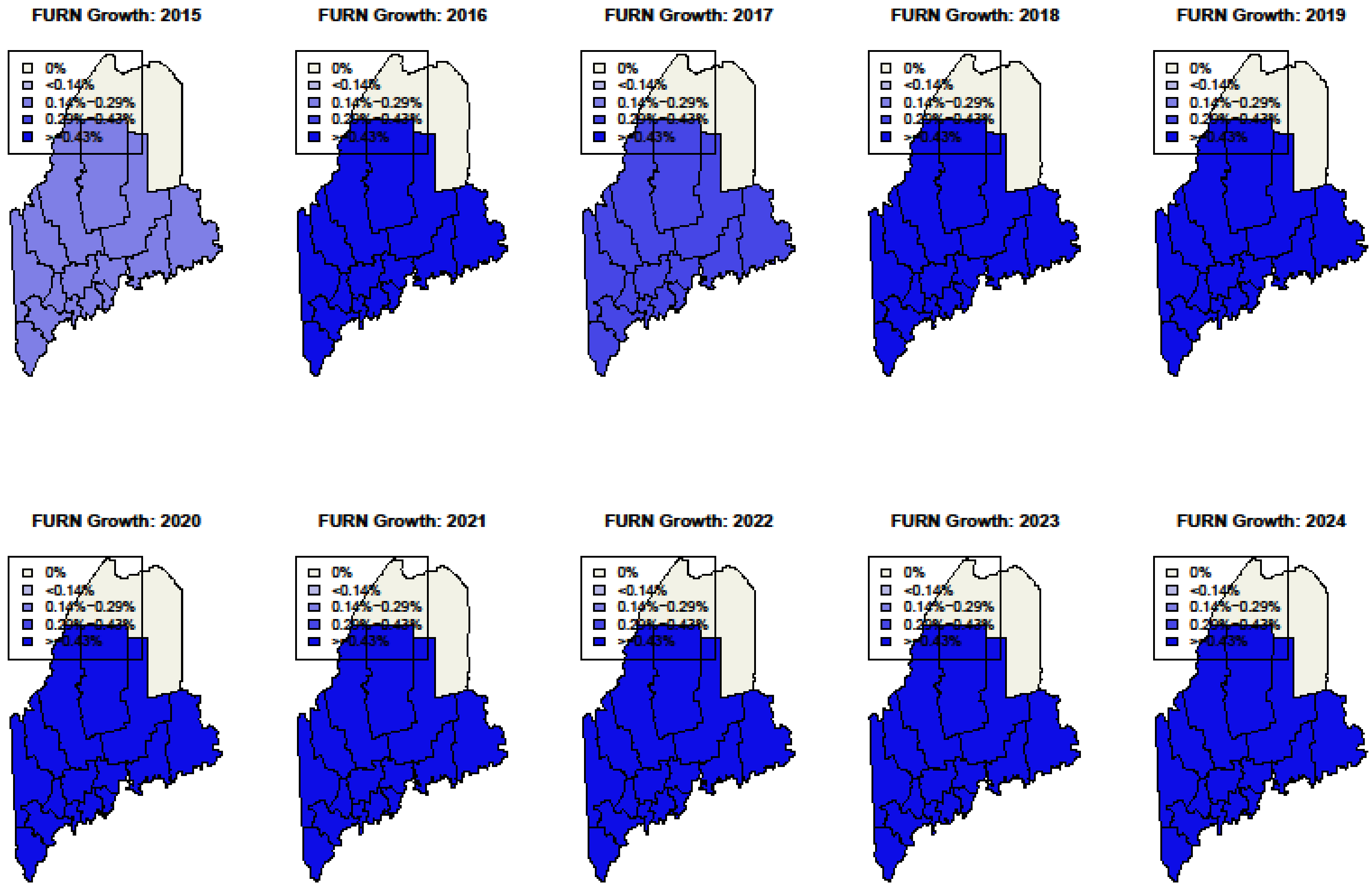

Figure 25. DR.SAGE baseline estimate of the change in furniture product output (FURN) by county.

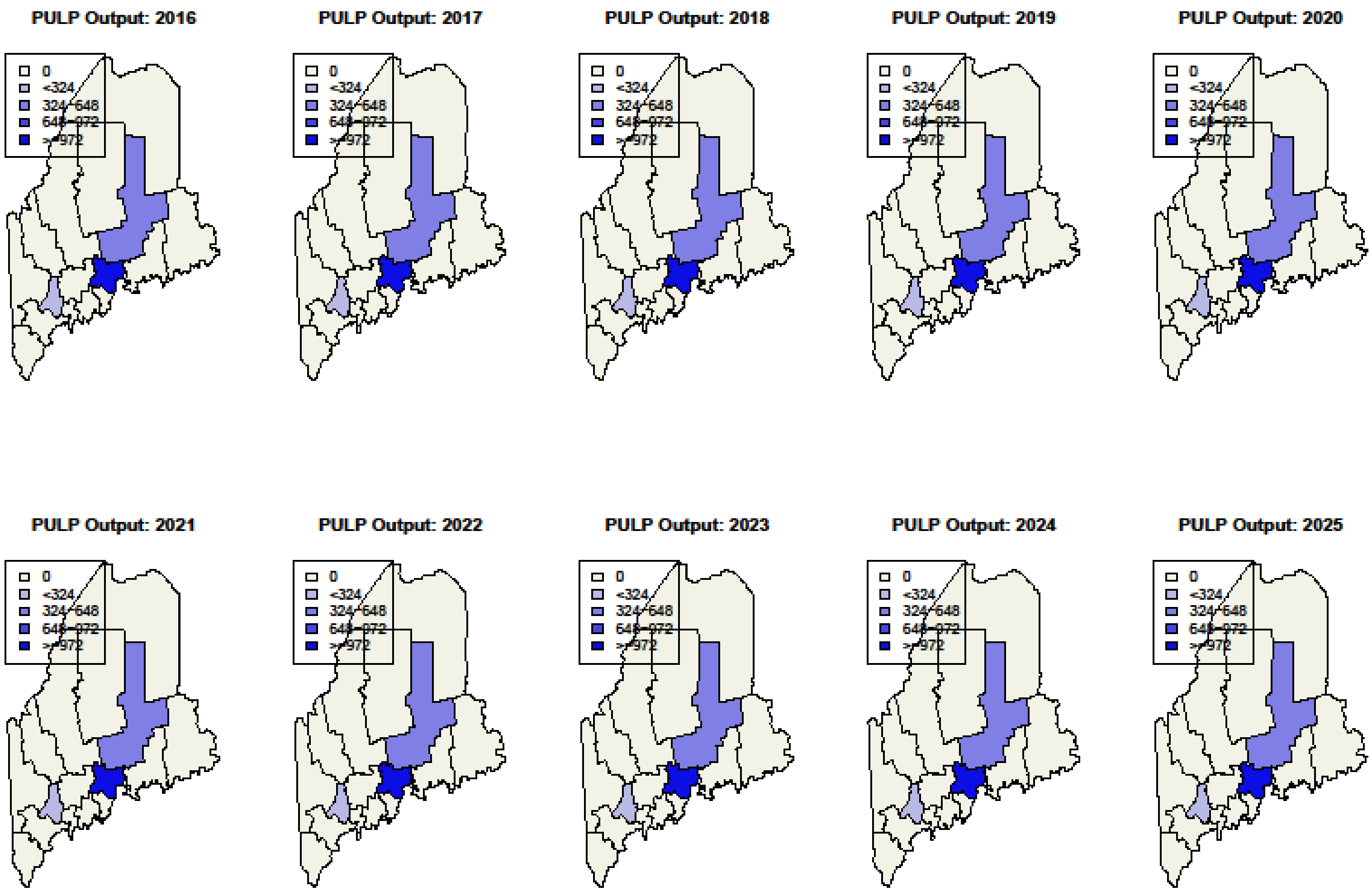

Figure 26. DR.SAGE baseline estimate of the output of pulp products (PULP) by county in thousands of tons.

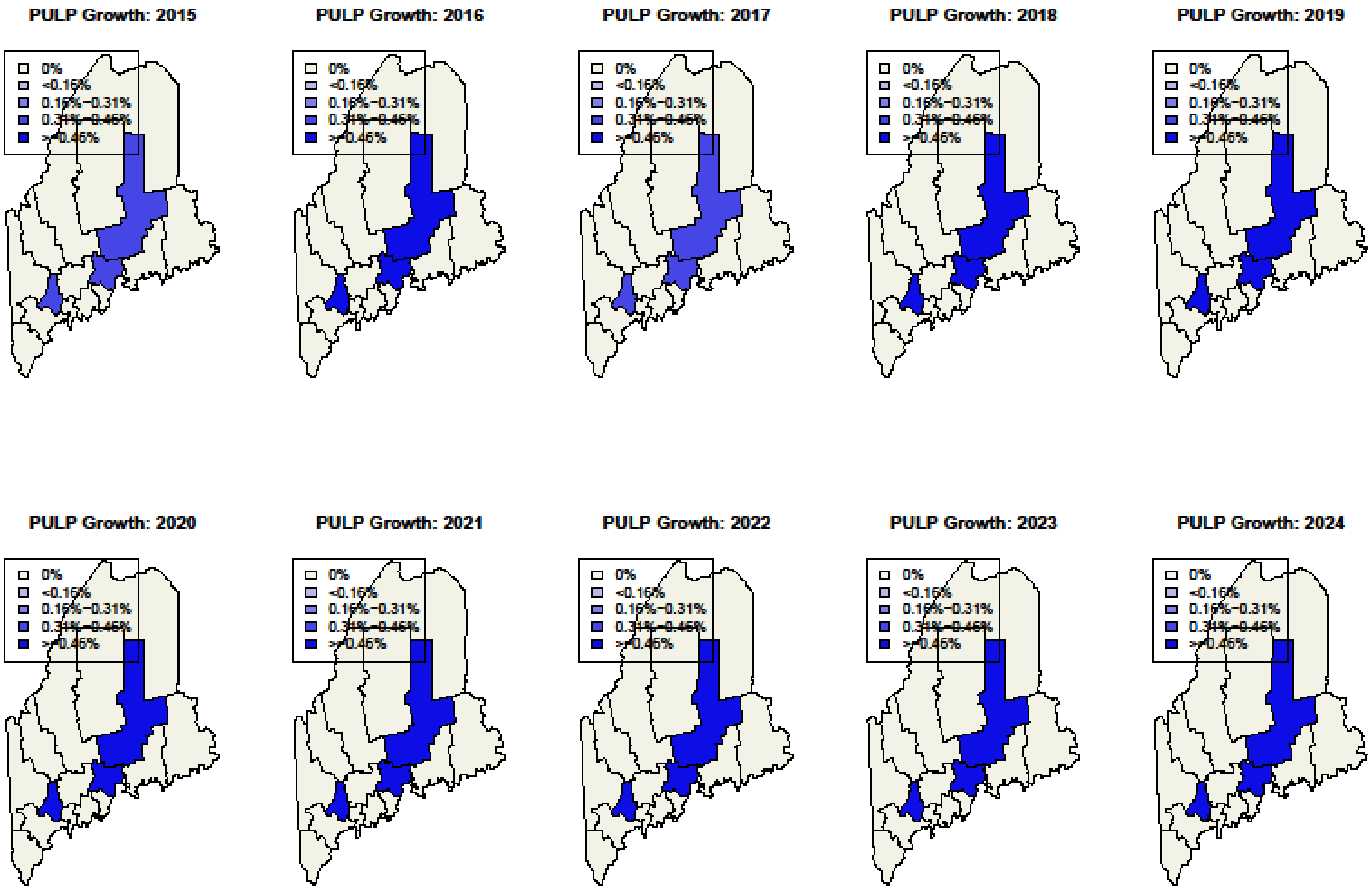

Figure 27. DR.SAGE baseline estimate of the change in pulp output (PULP) by county.

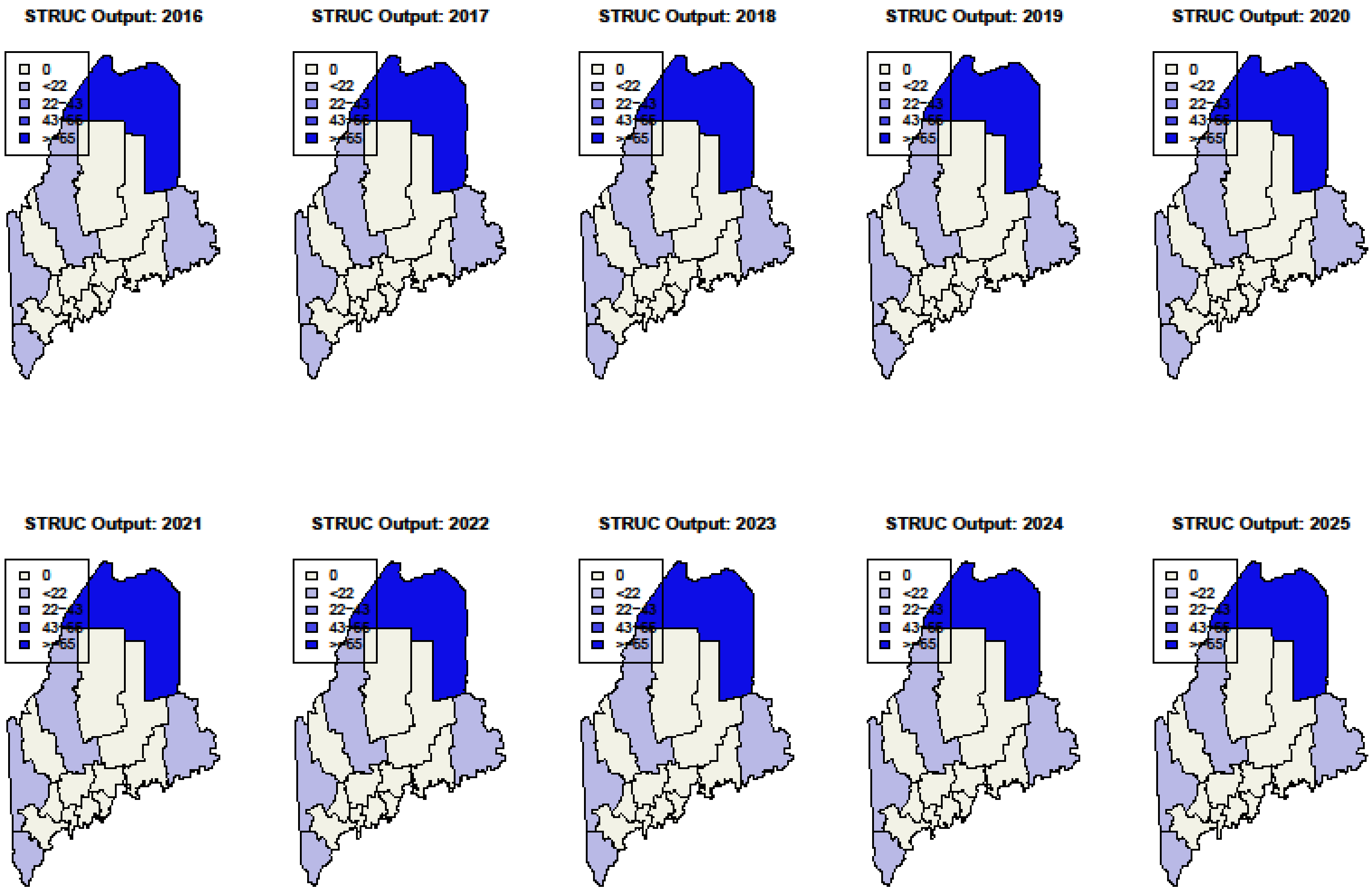

Figure 28. DR.SAGE baseline estimate of the output of structural wood products (SAW) by county in MMBF.

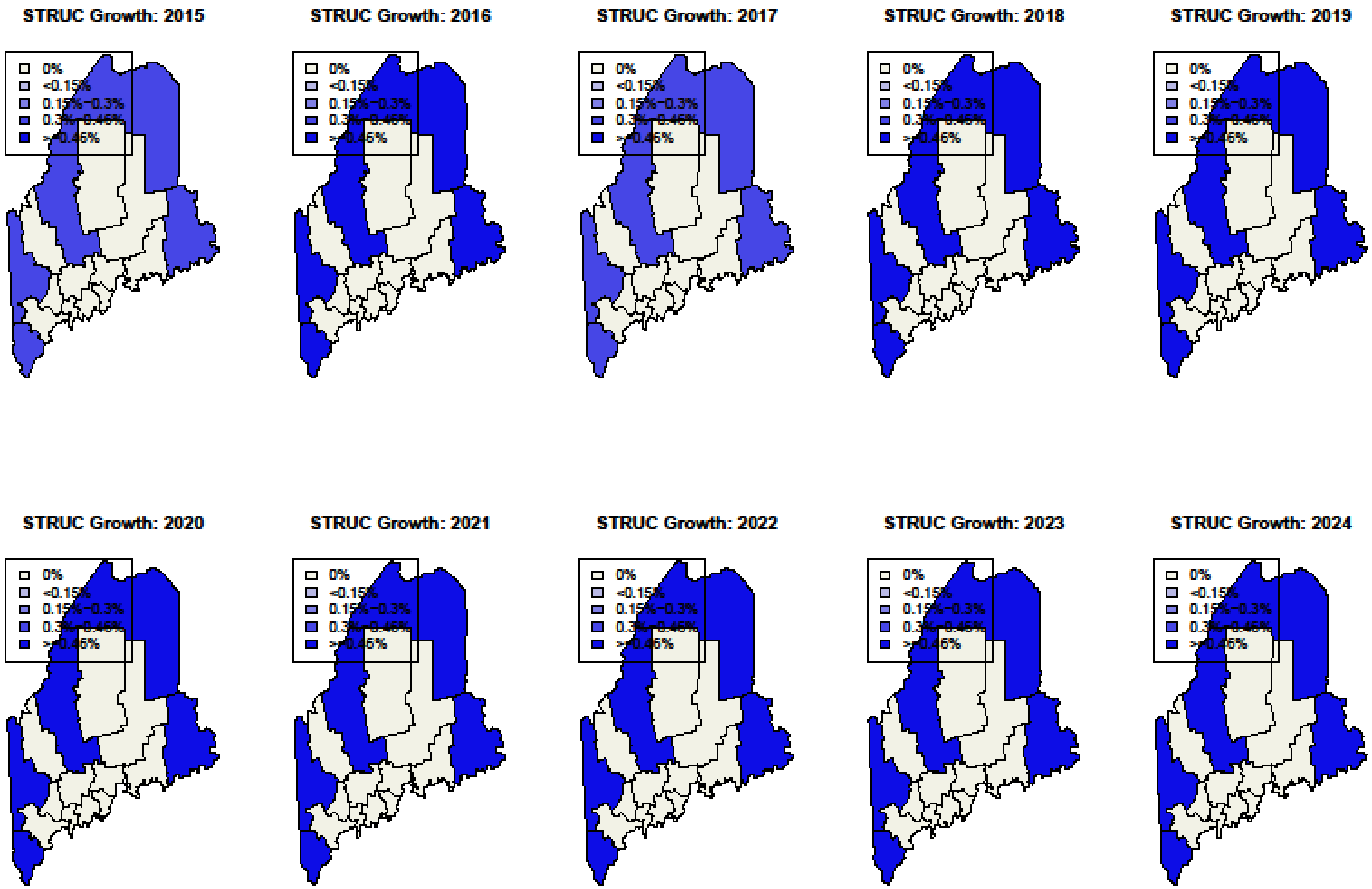

Figure 29. DR.SAGE baseline estimate of the change structural product output (STRUC) by county.

BIOGRAPHY OF THE AUTHOR

James Lavalette Anderson III was born in Wakefield, Rhode Island on January 2, 1992. They spent most of their youth in Wakefield, graduating from South Kingstown High School in 2010. James first attended the University of Connecticut, where they graduated with a dual Bachelor's degree in Mathematics-Statistics and Economics in 2013. They then earned a Master's degree in Statistics in 2015 at Virginia Tech. Finally, James began working on research at the University of Maine in 2016. Since then, they earned another Master's degree in Economics from the University of Maine. They are a candidate for the Doctor of Philosophy degree in Forest Resources from the University of Maine in May 2020.