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Handbook of Forest Resource Economics

Edited by

Shashi Kant

and

Janaki Alavalapati

HANDBOOK OF FOREST RESOURCE ECONOMICS

It is increasingly recognized that the economic value of forests is not merely the production of timber. Forests provide other key ecosystem services, such as being sinks for greenhouse gases, hotspots of biodiversity and areas for tourism and recreation. They are also vitally important in preventing soil erosion and controlling water supplies, as well as providing nontimber forest products and supporting the livelihoods of many local people.

This handbook provides a detailed, comprehensive and broad coverage of forest economics, including traditional forest economics of timber production, economics of the environmental role of forests and recent developments in forest economics. The chapters are grouped into six parts: fundamental topics in forest resource economics; economics of forest ecosystems; economics of forests, climate change and bioenergy; economics of risk, uncertainty and natural disturbances; economics of forest property rights and certification; and emerging issues and developments. Written by leading environmental, forest and natural resource economists, the book represents a definitive reference volume for students of economics, environment, forestry and natural resource economics and management.

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HANDBOOK OF FOREST RESOURCE ECONOMICS

Edited by Shashi Kant and Janaki R. R. Alavalapati

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1

EVOLVING FOREST RESOURCE ECONOMIC THOUGHT

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Abstract

This introductory chapter provides an overview of the contents of this handbook. First, a historical perspective of dominant forest economic thought is provided, and six themes of forest resource economics are identified. These themes are discussed in the form of six interrelated parts of the handbook. For each part, an overview is provided, followed by short reviews of its chapters.

Keywords

Bioenergy, climate change, ecosystems, forest economics, forest certification, natural disturbances, property rights, risk and uncertainty

Introduction

The links between forests and human beings are as old as the existence of human life on this planet. The origin of forest economic thought can be traced back to the early phases of *Homo sapiens* because forests have always been a resource for human welfare. As humans evolved from being hunters and gatherers through the agrarian and industrial eras to the information and technology era, formal concepts, principles and theories relating to forest economics have also evolved. As such, economic thought that was relevant and rational in one era may be irrelevant and irrational in another. There are situations in which some concepts, theories and technologies become dominant due to path dependence and positive feedback effects, whereas others remain dormant (Arthur, 1994). In addition, many path-breaking ideas and concepts are never transmitted from one place to another or from one culture to another due to communication and cultural barriers. Hence, it is impossible to trace the origin and evolution of forest economic thought.

Evidence suggests that Kautilya (or Chanakya) discussed some economic aspects of forest resources in his famous book *Arthashastra* (economics) written during the fourth century BC in India (Basu, 2011). It is also believed that the first discussion of economic harvesting in Germany was held in the monasteries of Mauermunster during the 1100s (Amacher, Ollikainen and Koskela, 2009). During the 1700s, Denmark and England played a dominant role in developing basic concepts of forest economic thought (Amacher et al., 2009). Danish Count C.D.F. Reventflow proposed an economic theory of optimal forest rotation as early as 1801 (Helles and Linddal, 1997). Englishman William Marshall, in his writings in 1790 and 1809, suggested the need to include the opportunity cost of growing trees and the cost of occupying the land in the calculation of optimal forest rotation (Scorgie and Kennedy, 2000). Irrespective of these early writings, the origin of current dominant forest economic thought is largely attributed to Martin Faustmann's paper published in 1849.

In the first half of the 1800s, many foresters of Germany, such as Friedrich Pfeil, Gottlieb König and Johan Hundeshagen, published economic aspects of forest management in the first journal of forest science, *die Allgemeine Forst- und Jagt Zeitung*, which was started in 1824 (Amacher et al., 2009). However, it was the article by Edmund von Gehren on the determination of land value published in the same journal in 1849 that attracted the attention of Martin Faustmann, who published his critique and offered a different approach to calculate land value in the same year. In 1850, Pressler supported Faustmann's approach with a mathematical formulation (Pressler, 1860). In 1921, Bertin Ohlin, a Swedish economist, also presented a mathematical formulation of optimal forest rotation (Ohlin, 1921). Hence, Faustmann, Pressler and Ohlin are considered the founders of forest economic thought, which remained unnoticed by the English-speaking world for almost a century. The earliest reference to Faustmann's formulation in English was Gaffney (1957), followed by Bentley and Teeguarden (1965) and Pearse (1967). Faustmann's paper was translated into English in 1968. Samuelson (1976) gave the credit for current economic thought to Faustmann's formulation, and since then, Faustmann's formulation has become the cornerstone of forest economics (Newman, 2002).

Irrespective of the origin of current forest economic thought, two aspects – optimal forest rotation and the choice of discount rate – have dominated discussions in forest economics for the past 50 years. The ownership of forests and the trade of forest products are two other aspects that have been discussed heavily. The issue of ownership has multiple aspects. About 75% of global forests are publicly owned, whereas about 14% are privately owned (White and Martin, 2002). In the case of public forests, determining optimal timber prices is a challenging economic issue because of a large single ownership that does not satisfy the conditions of a competitive market. In the case of private forests, the challenge is to design economically optimal tax policies to advance societal goals. Another complexity arises when different forest owners have different forest management objectives. Similarly, forest products have been locally and internationally traded for centuries, and an understanding of trade issues is just as critical as understanding the local economic issues associated with ownership.

Although the foundations of forest economic thought laid by German foresters mainly focused on timber resources, the importance of nontimber resources in decision making started to emerge in the 1970s. In 1976, Hartman incorporated nontimber resources in determining optimal forest economics rotation (Hartman, 1976). Since then, efforts to advance nonmarket evaluation techniques to quantify the value of ecosystem services such as outdoor recreation, biodiversity, clean air and clean water have been intensified.

Climate change seems to be the greatest environmental challenge of the twenty-first century. Forest carbon sequestration and storage has been shown to play a critical role in mitigating climate change. For example, Bonan (2008) found that carbon sequestration in forest ecosystems was close to one-third of carbon emissions from the use of fossil fuels and land-use change. Approximately 75% of total terrestrial biomass carbon and more than 40% of soil organic carbon are stored in forest ecosystems (Jandl et al., 2007). Hence, the economics of climate change must be an integral part of forest management and conservation strategies.

The risks and uncertainties associated with markets and natural processes such as climate change, forest fires and biological invasion of species have stimulated many forest economists to incorporate them into the analysis.

The Faustmann formulation assumes that a forest owner operates under the conditions of a 'private property' that includes exclusive, perpetual, transferable and unfettered property rights. Forest ecosystems provide a web of goods and services that include private goods, public goods, common-pool goods and club goods; therefore, a simple concept of resource ownership may not be good enough for economic analysis of forest ecosystems (Kant, 2000). In fact, government's role in regulating and managing forests arises due to the existence of multiple types of goods and associated market failures (Kant, 2003a). Forest ecosystems are specifically susceptible to market failures because they are expected to contribute not only to the private goals of the forest owner, but also to social objectives, including the state of the environment. Most governments play an active role in designing forest property rights arrangements to achieve private as well as social goals. Hence, the economics of forest property rights has become a very important component of current forest economic thought.

Finally, there are many economic aspects of forests that cannot be dealt with in the boundaries of the Faustmann framework, and that leads to gaps between theoretical economic models and forestry practices. Kant (2003b, 2013) observed that the economics profession, as a whole, has been re-examining and challenging almost every basis of neoclassical economic thought, in order to reduce the gap between theoretical models and practices. Hence, it is imperative for forest economists to extend the boundaries of forest economics beyond Faustmann's economic thought. The forest economics profession seems to have taken up this challenge by drawing concepts from other streams of economics, such as new institutional economics and political economy.

Keeping these six themes of forest economics in perspective, we have divided this book into six parts. Each part contains chapters focusing on specific issues related to its theme. There is some continuity, including linkages, among the chapters of each part; however, each chapter stands alone. Given the importance of the fundamental topics that have been the main attraction of forest resource economics for 60 years or more, we start this book with Part 1, focusing on fundamental topics, and close it with Part 6, which focuses on emerging issues and developments.

Part 1: Fundamental topics in forest resource economics

The focus of Part 1 is on four topics – Faustmann's formulation, rate of discount, ownership and international trade of forest products. In Chapter 2, Deegen and Hostettler note that although the Faustmann model is a useful tool for making an economic decision, the underlying process of market mechanisms, known as catallactics, is also very critical. The authors discuss theoretical concepts and provide an overview of selected contributions of forestry to the inner processes of market functioning. In Chapter 3, Chang discusses the generalized Faustmann formula that allows stumpage prices, stand volumes, annual incomes, regeneration costs and interest rates to vary from timber crop to timber crop. As a result, optimal management and/or optimal rotation would also vary from timber crop to timber crop. Chang notes that this formulation represents a more realistic world relative to Faustmann's world, in which everything remains static forever.

Price, in Chapter 4, highlights various economic and ethical perspectives associated with different economic justifications for discounting, such as opportunity cost, time preference, diminishing marginal utility, declining discount rate and internal rate of return.

Next, three chapters are focused on economic issues associated with ownership. In Chapter 5, Wear presents US forest policy history and forest economics research related to timber supply by ownership groups. He raises many important issues in light of new models of private ownership, such as Timber Investment Management Organizations (TIMO) and Real Estate Investment Trusts (REIT). Leefers and Ghani, in Chapter 6, focus on various timber-pricing mechanisms such as administered charges, negotiated values and market-derived prices – the residual value method and transactions evidence method – used by governments. Ollikainen, in Chapter 7, reviews the results of forest taxation in the Faustmann and Hartman framework, discusses best and second-best forest tax policies, and relates the discussion to modern forest policies promoting ecosystem services such as biodiversity benefits, climate mitigation and nutrient loading. Finally, in Chapter 8, Perez-Garcia and Robbins provide an overview of global forest products trade, discuss economic theory and empirical models of trade and present economic assessments of selected forest products trade policies.

Part 2: Economics of forest ecosystems

Part 2 covers three topics – valuation methods for ecosystem services, economics of specific ecosystems and payment mechanisms for ecosystem services. In Chapter 9, Boyle and Holmes provide an overview of valuation methods and expand on choice experiments. The authors present the latest information on choice experiment methodologies and then discuss their applications to forest ecosystems. The next four chapters are focused on the economics of different forest ecosystems. In Chapter 10, Montgomery and Crandall place old-growth forests within the context of the Faustmann and Hotelling models and discuss old-growth forest values and methods of their measurement. Poudyal and Hodges, in Chapter 11, focus on the economics of open spaces (or green spaces) in urban environments. In particular, they review measures of open spaces, valuation methods (with an emphasis on hedonic price method) and recent studies in open space valuation. Chapter 12 focuses on forest ecosystems that are used to manage game and recreational hunting. Here, Munn and Hussain present the institutional context of these ecosystems in the United States, insights about hunting lease markets of the south-eastern United States and economy-wide implications of wildlife-associated recreation activities. Mercer, Frey and Cubbage, in Chapter 13, focus on the economics of agroforestry systems and review economic principles and approaches to assess agroforestry systems and demonstrate their application through a case study. The focus of the last chapter in Part 2, Chapter 14, is on the status of payment for ecosystem services schemes in developing countries. In particular, Gong, Hegde and Bull discuss schemes for watershed services, biodiversity conservation and forest carbon and present lessons learned and future challenges.

Part 3: Economics of forests, climate change and bioenergy

There are three very important aspects associated with climate change and forests. First, climate change will impact the productivity of forests and thus the forestry sector. Second, forests can be managed to sequester carbon, thereby moderating climate change. Third, carbon emissions can be reduced by using wood as a source of energy and by reducing forest degradation and deforestation. In this part, economic issues associated with the previous three aspects are discussed.

Part 3 begins with Chapter 15, in which Sohngen discusses the potential impacts of climate change on forest ecosystems and reviews studies that have analyzed the impact of climate change on the forest sector. In Chapter 16, van Kooten, Johnston and Xu discuss economic issues related to the creation of forest carbon offset credits through forest management strategies and the problems associated with additionality, leakage, duration or impermanence and governance. Buongiorno, Bollandsås, Halvorsen, Gobakken and Hofstad, in Chapter 17, focus on the economics of carbon storage through uneven-aged forest management strategies and present methods to derive a schedule of supply for carbon storage. Lal and Alavalapati, in Chapter 18, discuss economic aspects of forest biomass-based energy, including forest biomass supply, public preferences for woody bioenergy, competition with traditional forest industries, land-use change and greenhouse gas emissions. Part 3 concludes with Chapter 19, in which Angelsen focuses on the economics of REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and presents four broad themes: REDD+ credits in international carbon markets, REDD+ as performance-based aid, national and local payment for ecosystem services and other national policy approaches to curb deforestation.

Part 4: Economics of risk, uncertainty and natural disturbances

Risk and uncertainty associated with natural phenomena, such as climate change, forest fires and biological invasions, and the growth process of forests and markets are important aspects of forest economics. In Chapter 20, Amacher and Brazee review the literature on risk and forest landowner decisions and elaborate on two themes – risk associated with future market parameters and risk associated with established forest stands being subject to natural or catastrophic events before harvest. Burkhardt, Möhring and Gerst, in Chapter 21, present a stochastic model that incorporates risk as a survival function to calculate land value and optimal rotation defined in terms of expectations suitable for a risk-neutral decision maker. In Chapter 22, Khajuria focuses on the applications of real options analysis to forest harvesting and conservation decisions. He discusses the literature that has modeled timber prices as the geometric Brownian motion, mean reversion, mean reversion with jumps and mean reversion with varying long-run marginal cost process. Strange et al., in Chapter 23, focus on economically optimal and biologically sound conservation decisions in an uncertain world and discuss theoretically consistent approaches that combine biodiversity and valuation modeling under uncertainty. Holmes et al., in Chapter 24, focus on the economic analysis of preinvasion and postinvasion management of biological invasions of forests under risk and uncertainty conditions and suggest new microeconomic and aggregate economic studies of damages caused by biological invasions across forest types and ownerships.

Part 5: Economics of forest property rights and certification

Some economic aspects associated with ownership are discussed in Part 1. However, the concept of property rights is so complex and issues are so diverse that it requires a separate part rather than combining it with other topics. In Part 5, four chapters are devoted to property rights issues – one chapter provides a broader and general perspective, and the other three provide national perspectives for Brazil, China and the United States. The last chapter deals with the economics of forest certification, which has some property rights implications.

Luckert, in Chapter 25, discusses various economic concepts relating to forest tenures, including rules as attenuations and subsidies, forest tenures and economic behavior, economic rent and market and government failures, and then explores the challenges in analyzing economic impacts of forest tenures. The focus of Chapter 26 is on the economics of the evolution of the Brazilian Amazon frontier. In this chapter, Sills discusses the historical drivers of deforestation, the Brazilian government policies that increased agricultural rents, new drivers of deforestation and current policy initiatives that seek to change the incentives by increasing tenure security for forest land, imposing penalties for illegal deforestation and creating new opportunities to earn revenue from standing forest. In Chapter 27, Zhang, Shen, Wen, Xie and Wang use changes in the bundle of rights to forests and forestland and the separation of use rights from ownership to examine the evolution of forest property rights in China. Ebers and Newman, in Chapter 28, focus on the economic analysis of conservation easements in the United States. They discuss landowner incentives for instituting conservation easements, methods for easement appraisal and ways to measure easement performance. In Chapter 29, Toppinen, Cubbage and Moore discuss the concepts, advantages and economic aspects of forest certification and corporate social responsibility and elaborate on the challenges of extending these approaches to smaller organizations and developing countries.

Part 6: Emerging issues and developments

The economics profession, as a whole, has been re-examining and challenging almost every basis of neoclassical thought in order to reduce the gap between theoretical models and practices or to increase the theory–evidence ratio. These efforts include the emergence of new streams of economics such as behavioral economics, evolutionary game theory and new institutional economics. Forest economists are also making similar efforts by incorporating these new streams of economics into forestry. The chapters of Part 6 are examples of such efforts. The first chapter in this part, Chapter 30, focuses on new institutional economics (NIE), and Wang, Bogle and van Kooten present an overview of the genesis, scope and main developments of NIE, with emphasis on property rights and contracting, transaction cost economics, moral hazard and information and principal–agent relationships. In Chapter 31, Zhang discusses various theories of political economy and their origin and reviews empirical studies of forestry in various countries. Kumar and Kant, in Chapter 32, provide an overview of game theory and review applications of game theoretic models to forestry issues such as people's participation in comanagement of forests, timber markets and interactions among stakeholders in the case of weak property rights. Gundimeda, in Chapter 33, emphasizes the need of expanded forest accounts and reviews two major approaches, namely, income as a return on wealth and income change as an indicator of welfare. Chapter 34 focuses on the applications of computable general equilibrium (CGE) modeling in forest economics. Banerjee and Alavalapati, in this chapter, present the application of a recursive dynamic CGE model to assess the regional economic impacts of Brazil's forest concessions policy in the Amazon.

We close the book with a chapter on twelve unanswered questions in forest economics. In this Chapter 35, Hyde observes that there are many situations in which Faustmann's formulation is either incomplete or inappropriate. The author identifies unresolved issues within the discipline of forest resource economics at the beginning of the twenty-first century and discusses two concerns – empirical assessment and incremental effects – for policy applications.

Conclusion

This is the first publication of a handbook of forest resource economics. We have tried to cover a wide range of issues associated with the subject, starting with fundamental topics and moving to recent emerging issues and developments. Each chapter provides a synthesis of the state of the topic covered and aims to be a comprehensive, up-to-date, authoritative source on the subject.

The current forest resource economic thought is more than 165 years old and is growing in many ways. The growth is largely coming because of an increased understanding of ecosystem services benefits for human welfare. Emerging global issues such as climate change, sustainable development and the green economy have provided further impetus to the growth and diversification of forest resource economics. The emergence of new streams in economics, such as agent-based computation economics, behavioral economics, complexity theory and economics, public choice theory and social choice theory, have also contributed to the growth of forest resource economics. Hence, it is impossible to cover all important topics in this volume, and we regret that.

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PART 1

Fundamental topics in forest resource economics

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2

THE FAUSTMANN APPROACH AND THE CATALLAXY IN FORESTRY

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Abstract

There exist two different classes of market theories. One class, which is the well-known standard microeconomics, deals mainly with the results of the market process. The Faustmann model belongs here: The optimal rotation length is the very result of market exchanges. The other class of market theory focuses on the understanding of the underlying process or, in the slogan of Vernon Smith, of the intention 'to make the "invisible hand" "visible"'. This class of theory is called catallactics. The key problems of catallactics are how individuals coordinate their decentralized knowledge through exchange, how prices carry that knowledge from individual to individual and how individuals discover new answers for unanticipated changes via market competition. Those questions are of major interest for understanding the complexity of forestry, contemporary and in the long term. Because catallactics is not as well established in forestry economics as its microeconomic counterpart, each section of this chapter comprises two parts. One part presents a brief introduction into the theoretical concepts of the market process from the catallactic point of view. The other part refers to, summarizes and systematizes selected contributions of forestry to the understanding of the inner process of coordination through selling and buying.

Keywords

Competition, coordination, entrepreneur, exchange, Faustmann model, human action, knowledge, prices, unanticipated changes

Catallactics, the economics for understanding the market process

This section is about the coordination of human actions through selling and buying applied to the field of forestry. The beginning of the study of this kind of coordination can be traced back directly to Adam Smith. He discovered that selling and buying leads to satisfactory results for any individual in the society. Moreover, in his two main books, *The Theory of Moral Sentiments* (Smith, 1759/1984, p. 184f) and *An Inquiry into the Nature and Causes of Wealth of Nations* (Smith 1776/1979, p. 456), he speaks of the market coordination as if guided by an 'invisible hand'.

The first study of the results of the 'invisible hand' with particular reference to forestry is *The Isolated State* by Thuenen (1826/1990). He analyzes land rents accruing from different land uses such as the production of vegetables, lumber and rye as a diminishing function of distance on an overall homogenous area surrounding a central town. At each distance, the landowner selects the product promising the highest rent. In consequence, the regular patterns of the cultivated landscape – the Thuenen rings – are the very result of market exchanges (cf. Niehans, 1998). The second important model for studying the effects of coordination through selling and buying in forestry is the Faustmann model (Faustmann, 1849), which is well known to every expert in forestry. A current survey of this type of analysis in forestry is provided by Amacher, Ollikainen and Koskela (2009).

Both the Thuenen and the Faustmann models allow studying the *results* of the 'invisible hand'. For understanding the *inner nature* of the 'invisible hand', which tries to make the 'invisible hand' 'visible',[1] there is another class of market theories.

The key questions of this class of theories include the following: How does the decentralized coordination of millions of human actions work without any central supervisor? How is the knowledge on the globe utilized, when it is not given to anyone in its totality but is separated among billions of individuals? How do individuals mutually adjust their individual plans of life in cases of unanticipated changes in the society? According to the suggestion of Whately (1832, p. 6), we name this class of theories catallactics.

Thus, there exist two different classes of market theories. One class deals mainly with the *results* of the market process, which is the well-known standard microeconomics. The other class focuses on the *understanding of the underlying process*, which we call catallactics. In this chapter, we do not deal with the standard microeconomic market theory, but, instead, we focus on catallactics, or the study of how the 'invisible hand' works.

Nevertheless, catallactics is not as well established in forestry economics as its microeconomics counterpart. Therefore, every section of this chapter comprises two parts. One part presents a brief introduction into the theoretical concepts of the market process from the catallactic point of view. The other part refers to, summarizes and systematizes selected contributions to the understanding of the inner process of coordination through selling and buying. One group of the selected papers is from the field of forestry economics, which investigates forestry-related problems of market coordination. The other group of papers is from other economic disciplines, which offer contributions for a better understanding of coordination through selling and buying inside forestry.

The two classes of market theories work differently, however, not because of the underlying assumptions and methodologies. They both understand market exchange as interactions of purposeful individuals, and both are based on the methodological individualism (Kohn, 2004, p. 308). Instead, the differences of the two classes of theories stem from their different intentions. While *result*-related theories produce explanations which are satisfactory in comparison to empirical data, catallactical theories are employed for understanding the inner nature of exchange.

Thus, the 'invisible hand' is essentially a wonderful metaphor for *result*-oriented thinking. *The Isolated State* by Thuenen and the Faustmann model apply these class theories equally. They study the *results* of the market process. These are a well-structured, cultivated landscape and an optimal rotation length as the very *results* of market exchange. Let us move now from the study of results to the study of the inner nature of exchange.

The coordination of decentralized knowledge through selling and buying

In his seminal paper 'The Use of Knowledge in Society', Hayek (1945) characterizes the economic problem of society as a coordination problem, but not as a problem of the allocation of scarce means among alternative ends. The coordination problem arises because the knowledge of a society is separated among millions, or nowadays billions, of individuals. Therefore, it exists only bitwise, incomplete, contradictory and changeable in the minds of those individuals. There is no central body in the world where the knowledge of the billions of individuals is collected.

The story *I, Pencil* by Read (2008) gives illustrative assistance by showing the complexity of coordination for the production of an ordinary pencil. Read (2008, p. 4) starts with the assertion that no single individual on this earth knows how an ordinary pencil would be produced.

Although the specialists in the pencil factory know how to assemble a pencil, they do not know how to produce all the essential inputs. Let us look at the wooden material of the pencil: It may have come from a Brazilian or an Indonesian forest or from a plantation in South Africa. A lot of knowledge and continuous management over many years are necessary to produce timber for an ordinary pencil. Which tree species are suitable? How many plants are necessary? What is the best stand density for trees to grow in the right quality and with enough timber volume? Or look at the 'loggers to fell the trees'. They 'depend on specialized, high-tech equipment, as well as coffee, meals, clothing, health care, and countless other goods and services to do their job adequately. The logging equipment is made, in part, from steel. So steelworkers had a hand in the making of pencils, too, whether they know it or not' (Heyne, Boettke and Prychitko, 2010, p. 100). The steel in turn is made from ore. Miners, maybe in Brazil, in the Ukraine, in Canada or anywhere may have mined it. Sailors and truckers have transported the ore and the steel and the pencil machine and the pencil. At last, all the different components which are necessary for the production of a pencil are the results of hundreds and thousands of specialists. All these foresters, miners, steel producers, pencil machine producers, color producers, sailors, truckers, and so forth, were involved in the production of the pencil (Deegen, Hostettler and Navarro, 2011, p. 358).

> None of the thousands of persons involved in producing the pencil performed their task because they wanted a pencil. Some among them have never even seen a pencil and would not know what it is for . . . These people live in many lands, speak different languages, practice different religions, may even hate one another – yet none of these differences prevented them from cooperating to produce a pencil.
>
> *(Friedman and Friedman, 1990, p. 12f)*

For visualizing the market process, we prefer a graph in which a single bilateral exchange among two parties is embedded in and related to many other bilateral exchanges (Figure 2.1) (cf. Vanberg, 1995, p. 47ff). Clearly, such a network diagram is only a small window of the countless bilateral exchanges which we call 'market'. It illustrates that every change in a single bilateral exchange affects all the other bilateral exchanges, sometimes slightly and sometimes stronger. However, every single change will be absorbed by the system while the individuals adjust their exchange actions and balance them with the other bilateral exchanges. In this manner, the gigantic network of bilateral exchanges is always and continuously in a never-ending movement in which individuals coordinate their individual plans through selling and buying.

A recent paper by Buongiorno, Raunikar and Zhu (2011) may serve as an illustration of the complexity of the decentralized coordination through markets. Buongiorno et al. (2011) show the projection of consequences for the global forest sector of doubling the rate of growth of bioenergy demand relative to a base scenario by applying the Global Forest Products Model

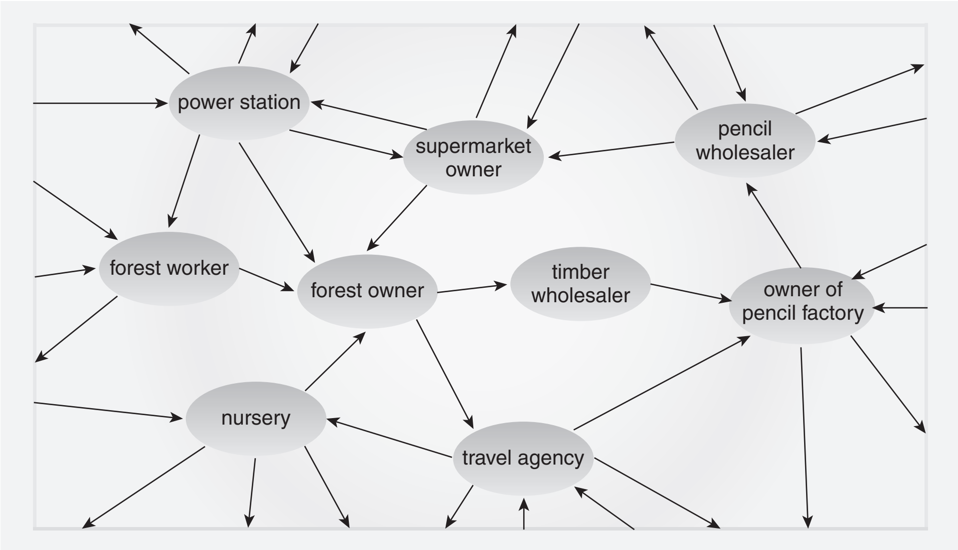

Figure 2.1 A network diagram for visualizing the coordination through market exchange.

(GFPM). They show, for instance, the prediction of the GFPM for the global forest stock change. Countries with the highest increases in fuelwood consumption, such as New Zealand with 364%, Germany with 334% and Canada with 329%, face only minor or even no reductions of their national forest stocks (i.e. 2%, 2% and 0%, respectively). As a consequence of the complex interdependencies of the global wood and bioenergy trade, forest stocks will decline significantly at completely different places of the world, such as in India by 50%, in Nigeria by 35%, in South Africa by 14% and in Indonesia by 10%. Although this study is far away from the complexity of the real world, it provides a little insight into the interweavements of global exchange.

Any concrete sale or purchase by an individual is embedded in and balanced with all other sales and purchases by the same individual (Figure 2.1). That means that each sale and each purchase unintentionally includes knowledge and preferences of all goods and services which the individual exchanges. To buy the ordinary pencil discussed previously is not only an action in the pencil market. Instead, it is an action that is simultaneously balanced with all other actions of the individual. Tullock (2005, p. 121) writes that the single individual makes something on the order of 15,000 to 20,000 buying decisions annually. This is a gigantic flow of information.

Illustrative forestry examples of the complexity of an ordinary individual action are also provided by studies of the determination of optimal rotation length of nonindustrial private forest owners when in situ preferences (Tahvonen and Salo, 1999), borrowing constraints (Tahvonen, Salo and Kuuluvainen, 2001) and nonforest income (Tahvonen and Salo, 1999; Tahvonen et al., 2001) are included. Because in those papers the same numerical example is applied, it can be used as an illustration for simultaneous balanced actions. The numerical examples in those papers show an optimal Faustmann rotation length of 83 years. However, considering the three components mentioned previously, the optimal rotation length ranges between 65 years and infinite, and it depends on the personal circumstances of the single forest owner.

Moreover, the single individual has to adjust his or her sales and purchases to the sales and purchases of the exchange partners. Therefore, buying the pencil is not only balanced with other actions of the single individual, but also adjusted to all sales and purchases of the store owner. The bilateral exchange is a result of various balancing actions of two involved parties.

Furthermore, the single sale or purchase is not only adjusted to the actions of the exchange partner, but strongly coupled with the other exchanges with the exchange partners of the exchange partner. For instance, the action of the customer of the pencil is not only coupled with the actions of the store owner; it also is coupled with the owner of the petrol station who sells petrol to the trucker who in turn transports the pencils from the wholesaler to the store.

Prices as carriers of knowledge in society

Prices

The complex, decentralized coordination of millions of individual actions through selling and buying takes place without any collection of all the knowledge in any single mind. It is not used in its totality in the contemporary society but is separated among millions of individuals. Usually, the single individual does not know all that much about the particular needs of her exchange partners. And the question arises, how can the single individual contribute to the satisfaction of the needs of which she does not know, and even satisfy those of individuals whom she does not know?

The carriers of this information are the prices, which are the results of previous and successful exchanges. The single individual can only become acquainted with those aspects of the many other unknown individuals which are reflected in these prices.

Let us imagine for a moment a well-working forest market, in which at every moment thousands of forest owners sell thousands of forests, and where most of these are immature. In this way, thousands of individuals become forest owners by buying forests.

Consider that the optimal rotation length is 50 years. Only the owners of the 50-year-old forest stand watch the prices for timber and for bare land. However, the sellers of the 49-year-old forests do not watch the prices for timber and bare land; instead, they watch the prices for 49-year-old forests. Only the buyers of these 49-year-old forests watch the timber and bare land prices and use this knowledge for their own asks in the market of 49-year-old forests. In the successful cases of selling and buying in the market of 49-year-old forests, the realized prices for the 49-year-old forests contain some information about the timber and bare land prices, which are necessary for the 50-year-old forest utilization.

In the same way, the sellers of the 48-year-old stands do not watch the prices for timber and bare land; they watch the prices for 48-year-old forests. The buyers of the 48-year-old forests also watch the prices of the 49-year-old forests and use this knowledge for their own asks in the market of 48-year-old forests. The realized prices for these 48-year-old forests contain some information about the prices of the 49-year-old forests, which again contain some information about the timber and bare land prices at the rotation length, and so forth.

Like a cascade, the forest prices carry stepwise the timber and bare land prices from the older to the younger forests and, finally, to the planting action through selling and buying of forests. From individual to individual, the prices of forests carry the knowledge 'which [enables] the sellers and the buyers to provide for needs of which he has no direct knowledge and by the use of means of the existence of which without it he would have no cognizance . . .' (Hayek, 1976, p. 115).

In the Faustmann model, the complex price cascade of the forests exchanges through markets is reduced to the beginning and the end point of the price cascade. It combines only the final timber and bare land price as the beginning of the price cascade and the planting cost as the end of the price cascade. As in every model, reductions in the Faustmann model are made for analytical reasons in order to find out the overall result of the market exchange but not to study the complex coordination through markets as a combination of many different sales and purchases.

However, the reduction of the price cascade to the beginning and the end point in the Faustmann model does not mean that the knowledge of timber prices at the end of the rotation is necessary at the moment of planting. With the help of prices, market exchange means exactly the opposite: to confine attention to the immediate circumstances of the individual actions.

The forest owner does not plant young trees because she knows that anybody will need wooden goods in 50 years. Instead, she plants trees because she expects that other individuals will buy her young immature forest stand when she sells the forest for various reasons, or as in the famous phrase by Samuelson (1976, p. 474): 'Even if my doctor assures me that I will die the year after next, I can confidently plant a long-lived olive tree, knowing that I can sell at a competitive profit the one-year-old sapling'.

For the same reason, an individual will buy an immature forest stand and conduct some precommercial thinnings, not because he knows which sorts of timber the demander at the time of the final rotation length will prefer. He conducts precommercial thinnings because he expects that another individual will buy the thinned forest stand for a satisfactory price (cf. Hayek, 1976, p. 115f).

Clearly, such a pure market process of many simultaneous exchanges of forests is a simplification because all these exchanges take place with some time lag: A forest owner plants trees not because he expects that other individuals will buy his young forest stand now and today, but, rather, he expects that other individuals will buy his forest stand someday in the future. As a consequence of unanticipated changes between the time of sale and the time of purchase, prices will change.

> It is these differences that bring about money profits and money losses . . . His (the entrepreneur's) success or failure depends on the correctness of his anticipation of uncertain events. If he fails in his understanding of things to come, he is doomed. The only source from which an entrepreneur's profit stems is his ability to anticipate better than other people the future demand of the consumers. If everybody is correct in anticipating the future state of the market . . . neither profit nor loss can emerge . . .
>
> *(Mises, 2007, p. 290)*

The adaptation of individuals to unanticipated changes by continuous price changes implies that the price cascade of forests is always in movement. Prices are not only the carriers of knowledge. Through selling and buying, the individuals substitute obsolete knowledge with new knowledge caused by the unanticipated changes. Thus, prices not only carry the knowledge, but also continually actualize the knowledge as well.

Nevertheless, the picture of thousands of simultaneous forest exchanges through markets illustrates how prices carry the information from exchange to exchange. When the forest owner sells an immature forest stand, it is neither possible nor necessary for him to have information on the future uses of this forest. Prices carry and actualize the whole complex of human knowledge and wants from individual to individual. When the individual considers the prices, he adjusts his individual actions with all the countless exchanges of all the other sellers and buyers. Nobody needs the information on the final needs, either for the present or for the future.

An illustrative case study for showing how individuals apply buying and selling for adjusting their living circumstances is the 'owner-consumer decisions on an amenity forest' by Christensen (1982). He describes the story of a New York businessman who bought a forest property with a number of different specific goals in view: He desired a rural retreat for his family as well as a secluded business place to bring associates for conferences together, and he anticipated horseback riding on the old logging roads. Time passed, his children grew up, other circumstances in his life changed and his aims shifted or deteriorated. The forest became more and more useless. Finally, after 12 years, he sold his forest property. In other words, he adjusted his asset endowments to his changing living circumstances in the long run by market exchange.

A careful step toward an understanding of how prices work as impersonal guides for individual actions is the generalized Faustmann model by Chang (1998), which is based on the Faustmann school of thought. In this model, a clear distinction between current and future prices with respect to the optimal rotation length is realized. Nobody knows or needs the prices of timber and production factors of future rotations. Instead, current land prices are used as the only available estimation of future land uses. This thinking is extended by price and product class watching during the time (Chang and Deegen, 2011).

Although exchanges through markets are independent of the ages of the sellers and buyers, they comprise intergenerational transfers of forest stocks. The buyer can be older or younger than the seller of the forests. It follows that some exchanges of forest stocks are exchanges among generations, and others are exchanges within the same generation. Every sale of forest stock from an older to a younger individual and vice versa is a smooth intergenerational transfer. This type of intergenerational exchange, however, is totally different from intergenerational transfer by bequest, which can be often observed in forestry and which is studied with overlapping generation models (cf. Amacher, Koskela and Ollikainen, 2002). These two types of intergenerational transfer should be clearly distinguished.

Learning by acting

Prices are the carriers of information and the transmitters of coordination, as we have demonstrated previously. Catallactics deals with the questions of how information comes into the prices and how the exchange through selling and buying utilizes information (cf. Smith, 2006, p. 2f).

For answering these questions, it is necessary to understand the learning process of individuals when they sell or buy. Market learning does not mean primarily reading, thinking and writing, as academics commonly do. In contrast, individuals in the market learn by acting, watching and listening. Literally in an endless feedback process, they realize the results of exchanges and repeat them in the same or an adapted manner. Experimental economics tries to make visible the learning process through selling and buying with the help of laboratory experiments (e.g. Smith, 1991). For the demonstration, an experiment inside the double auction institution is used (Figure 2.2).

> This trading institution, used throughout the world in financial, commodity and currency markets, is a two-sided multiple unit generalization of the ascending bid auction for unique items. Buyers submit bids to buy, while sellers submit offers or asks to sell, with a rich rule structure for defining priority based on price, quantity and arrival time . . . Notice that the demand crosses the supply at a range of market clearing prices, where demand = supply = 10 units, given by the interval (356, 360). Any whole number in this interval is a competitive equilibrium price. Only you and I know this, the subjects in this experiment know nothing of these facts . . . The subjects were inexperienced, meaning that none had previously been in a double auction experiment . . . The behavior shown in the right panel of Figure 1 is typical.
>
> *(Smith, 2006, pp. 4–5)*

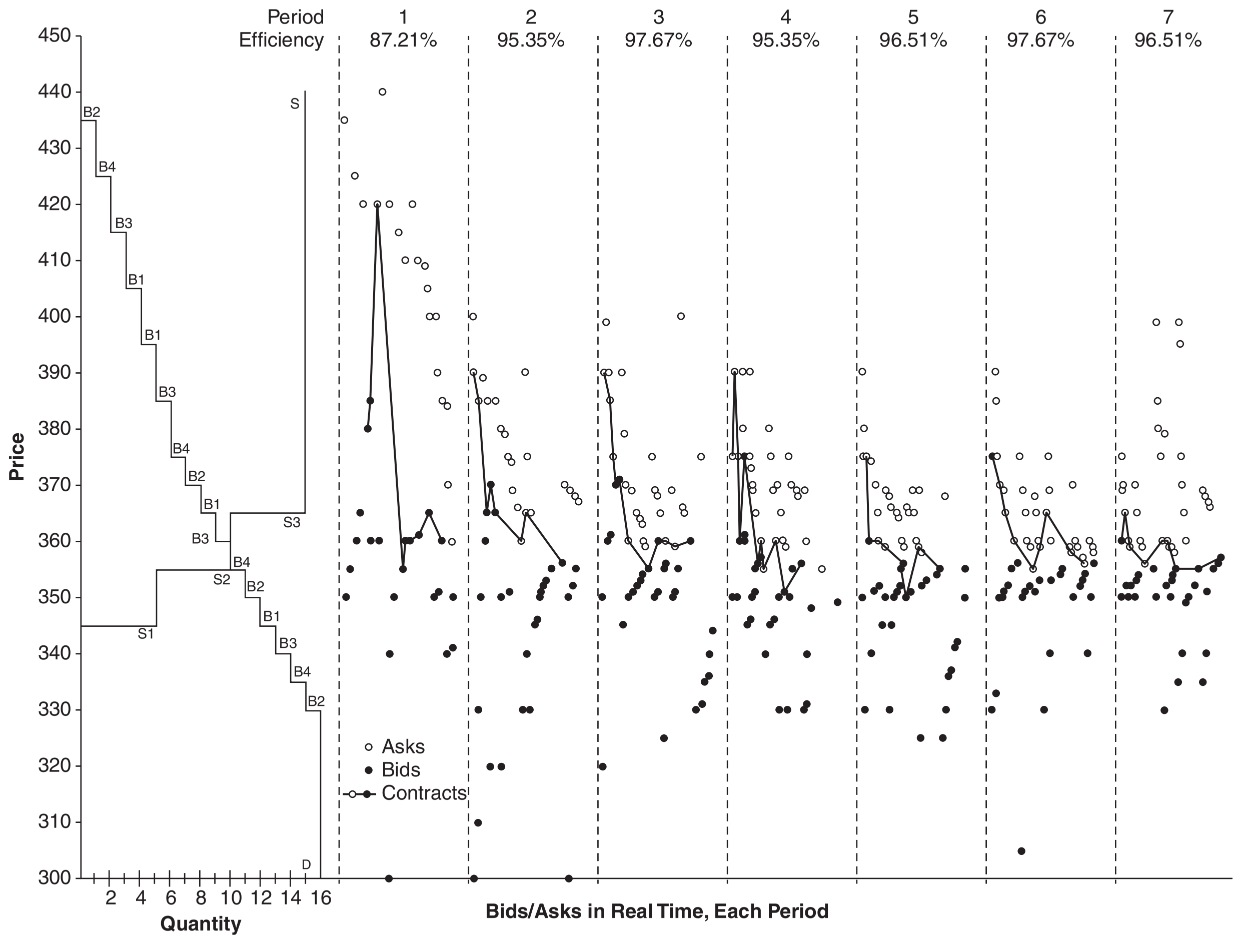

Figure 2.2 A double auction experiment. The economic environment for four buyers and three sellers is shown on the left. On the right, the sequence of bids, asks, and contracts in each of the first seven periods of trading is shown.

Reprint of Figure 1 in Smith (2006), with permission of John Wiley and Sons, Inc.

At the beginning, no participant has any idea about a 'realistic' bid or ask because there was not an auction before. Their offers come only from their individual wants and the initial expectations of the other participants. As a result, only a few bids find asks for an exchange contract. Most of them will be disappointed. Some of them do not adjust their individual expectations; others will change their asks or bids respectively. The successful traders learn as well. Their cognition involves that their expectations on the prices of other participants were not too bad. However, from period to period, the participants learn more and more about their own preferences and about the expectations of competitors and of trading partners via their own successful or unsuccessful trials of exchanges. During the periods, the participants learn more and more to coordinate their own actions with the actions of the other participants. During the periods, more and more bids and asks become successful. Or, in economic terms, the exchange process converges to the market equilibrium. The underlying way of learning is trial and error of acting, watching and listening, and of subsequent correcting or continuing.

During the bids and asks, individuals not only discover a little about how other individuals valuate goods. They often discover their own values that they give for the goods as well. After selling or buying, people are often astonished at how much they have paid for a good that they had valuated with a trifling amount of money at the beginning of the auction.

The evidence from approximately 150 to 200 individual economic experiments, conducted by many different researchers, studied for stationary, cyclical and irregular shifts in demand and supply in a wide spectrum of market institutions, such as posted-price, bilateral-bargaining games, continuous double auctions and others, shows that the participants converge with astonishing speed to the competitive equilibrium price and quantity (Smith, 1991, p. 226).

Thus, the microeconomic market theory is supported by the results from experimental economics: Market equilibrium is the consequence of the learning of individuals during the acts of selling and buying. From period to period, the participants watch their own success or failure to buy or to sell as well as the realized prices from the previous period, adapt their bids and asks in the present period to these observations and act again. Thus, the experiments visualize the learning process of the individual at the market.

Moreover, the many laboratory experiments with the wide variations of exchange rules show that no assumptions of price taking and of complete information are necessary for convergence to the competitive market equilibrium (Smith, 1991, p. 232). On the contrary, prices and quantity converge best to equilibrium under private incomplete information. Under complete information, the convergence process either fails or does less well (Smith, 1991, p. 803). Thus, the economic experiments support Hayek's (1945) hypothesis: 'The most significant fact about this (price) system is the economy of knowledge with which it operates, or how little the individual participants need to know in order to be able to take the right action . . .' (pp. 526–527). Or, in the words for testing the hypothesis at experimental markets, 'Strict privacy together with the trading rules of a market institution is sufficient to produce competitive market outcomes at or near 100% efficiency' (Smith, 1991, p. 223). These findings are also valid in the case of intertemporal competitive exchanges, which are typical in forestry (Miller, Plott and Smith, 1991).

In summary, selling and buying is a process in which individuals bring their own personal plans in accordance with the plans of the competitors and the exchange partners by learning stepwise with help of trial and error. Between the periods, prices carry and actualize the information of the exchange participants. The invisible hand of Adam Smith is nothing more than the learning process of humans by the trial and error of their actions.

As a consequence, the economic research on market exchange (microeconomics and catallactics) is on the right track. It shows that markets work in the way we think: Individuals coordinate their dispersed actions by selling and buying in a way that is self-regulating. Often enough, this coordination is much better than we expect from the standard market models (cf. Smith, 1991, p. 802).

Competition as a discovery procedure for finding answers to unanticipated changes

The existence of unanticipated changes is so extraordinarily prominent that Hayek wrote in his seminal paper, 'Competition as a Discovery Procedure': 'It is useful to recall at this point that *all* economic decisions are made necessary by unanticipated changes . . .' (Hayek, 2002, p. 17).[2] These unanticipated changes ask for adaptation of the individual plans as well as for readjustments of the individual plans with all other individual plans of the other individuals.

Prices are the carriers of information to show which of the changed circumstances ask for adaptation and adjustment and which do not. They show the single individual 'that what they have previously done, or can do now, has become more or less important . . .' (Hayek, 2002, p. 17) because the change of prices changes '. . . the compensation of the various services . . . without taking into account of the merits or defects of . . .' (Hayek, 2002, p. 17) the involved individuals. 'The most important function of prices, however, is that they tell us *what* we should accomplish, *not how much*' (Hayek, 2002, p. 17).

The seminal paper 'The View from John Sanderson's Farm: A Perspective for the Use of the Land' by Hugh M. Raup (1966) illustrates the land-use process as a result of unanticipated changes and their ensuing adaptations.

In 1740, the first settlers entered the virgin forest landscape of Petersham in central Massachusetts and started with subsistence agriculture in only small parcels. From 1791 to 1830, settlement continued, the regional road system in the landscape became a developed net, industrial towns grew and flourished continuously, regional markets evolved and agriculture changed from subsistence to a regional market economy. In other words, Petersham prospered. By 1850, the region was a full agricultural landscape with only a small amount of forest area.

In 1830, the opening of the Erie Canal changed the economic conditions: Settlers moved west. Railroads completed the traffic network, including changes from a system of isolated regional nets to a national network. Foodstuffs, in far greater quantity and produced more cheaply due to superior soil qualities in the west, were transported from western to eastern states. At the same time, these expansions attracted large sums of eastern capital for investments into mechanization and industrialization. As a result, Petersham's agriculture became uncompetitive; its economy collapsed. Over the decades, farmers emigrated. Agricultural use of the land was abandoned. Therefore, forests of nearly pure white pine came back by natural seeding. In 1900, Petersham was a full forest landscape again, yet without any value for the individuals who owned these former agricultural properties. However, some individuals discovered the value of the 'green gold'. As a consequence, the great logging and milling era between 1900 and 1920 arose in southern New England, with a new and a much higher prosperity than 100 years before.

The changes in prices as results of unanticipated changes do not lead only to a more or less unconscious balancing of the changing circumstances in everyday life. More importantly, the changes in prices offer incentives for discovering new solutions.

The fact that the white pine in Raup's (1966) paper becomes a raw material for containers, which were in high demand during the time of US industrialization, has nothing to do with the trees themselves. White pine had existed for a long time; it existed long before humans existed. Primarily, white pines were natural things, but not good for humans. Humans discover which of the billion different things in nature are goods. In the case of Raup's white pine, the pines came to maturity at the moment individuals demanded wood containers. Likewise, property owners from Petersham became aware that pines could be the raw material for those containers. Other people found niches in the price and wage structures of those days whereby the whole harvest process became economically feasible (Raup, 1966, p. 8).

> They all had first to be conceived in people's mind; then they had to be made attractive to investors so that capital would flow into them. A century earlier or even 50 years earlier, all that pine would have had very little value and most of it would, of necessity, have been cut down and burned to get it out of the way for farming.
>
> *(Raup, 1966, p. 8)*

In our economic analysis, we often reduce the adaptation to unanticipated changes to the rearrangement of the basket of the given goods according to the new price circumstances. But goods are not given. They are the result of human action (Hayek, 1948, p. 100f). Through market exchange, individuals do not make use of given knowledge. They discover, e.g. which natural things are goods, which technologies are most suitable for transforming things into goods, and so forth.

One great discovery in human history was the way to utilize ordinary trees as a raw material and as fuelwood because they existed at different places in the world in ancient and historical times in inconceivable dimensions in nature. Wooden raw material and fuelwood were not given as natural resources; instead, humans have discovered wood as material during history: Lips (1947) collected examples from the Stone Age and earlier of how humans discovered wood as common material.

Again, from century to century, individuals discovered more and more useful utilizations for this natural material (Perlin, 1997). When timber became scarce, humans were not troubled by this circumstance; instead, humans discovered substitutes and invented silviculture, the technology for producing 'natural' raw material. Kuester (1998, p. 69) remarks that the fast expansion of hazel after the Ice Age was a result of active 'silviculture' by humans during their resettlement of Central Europe. Koepf (1995/1996) notes that humans harvested forest trees in regular cutting cycles in the Modern Stone Age up to 4000 BC in southwest Germany as well as in Etruscan iron mining since 700 BC.

A recent example of discovering things as goods is the story of forest amenity evolution during the nineteenth and the twentieth centuries: Although forest scenic beauty has existed since time immemorial, the discovery of forest landscapes as a source of amenity services is a product of modern times (Mises, 2007, p. 645). Figures in Duerr (1993, p. 101), as well as in Anderson and Hill (1996, p. 516), give related illustrations of the increase in visitors to national parks during the twentieth century. Butler and Leatherberry (2004) show that the number of family forest owners in the United States has increased, and that the most common reason for these ownerships is enjoying beauty and scenery.

In the competitive market exchange, individuals also discover new technologies, new organizational solutions and new forms of cooperation as better answers to unanticipated changes. A typical example is silviculture, the forestry technology to reduce timber scarcity and boost forestland competitiveness. During the last 150 years, forestry practitioners have reduced the production time for timber (rotation length) from approximately 400 to 600 years (200 years ago) to nowadays 5 years in some forest plantations. According to Morozov (1928), forest practitioners first replaced succession with man-made forest regeneration. Secondly, they replaced slow-growing trees (oak and beech in Central Europe) with fast-growing trees (spruce and pine in Central Europe), and actually, they introduced biotechnology innovations (Sedjo, 1999,

p. 18f). That means forest practitioners have reduced interest costs for timber production of about 10^{13} euros/ha during the last 200 years, assuming a continuous interest rate of 5%.

An example of discovering new organizational solutions is the outsourcing of harvesters and forwarders. As an adaptation of vertical organization of forestry enterprises in Central Europe, they reorganized into specialized timber harvest companies. Before the introduction of harvesters and forwarders en masse, when harvest machines were mostly chainsaws, the timber harvest was typically part of forest ownership. After the introduction of harvesters and forwarders, both the capital cost and the cost of specialized knowledge and specialized organization increased and asked for adaptation. The adequate answer that forest enterprises found was the outsourcing of harvesters and forwarders and the foundation of specialized harvest companies.

An example of discovering new institutional arrangements as a reorganization of existing property rights is the story of conservation easements by forest trusts in the United States:

> [E]asements are based on the idea that property ownership is not a single indivisible right, but instead a collection of individual, often separable, rights. These individual rights include, for example, the right to erect structures, reside, grow crops and exclude other from property . . . The advantage of easements over ownership for land trusts is that they allow trusts to protect lands, not by acquiring the entire bundle of landowner rights, but by acquiring only those specific rights that are relevant to the trusts' conservation goals.
>
> *(Clark, Tankersley, Smith and Starnes, n.d., p. 2)*

The acting human: The maximizer and the entrepreneur

The underlying economic model of human action is the homo economicus: The individual maximizes her or his utility subject to constraints. This model is applied to the Faustmann model: The landowner maximizes the land expectation value with respect to the rotation length. Many different variations study various maximization and optimization problems, such as the optimal planting density (Chang, 1983) or the optimal choice between even- and uneven-aged forestry (Tahvonen, 2009).

The objective(s) is given, just as all involved products and production factors and their prices. The landowner in the Faustmann model knows every timber sort of her standing trees, knows every environmental service of her forest, which she can sell for known prices. Also, she knows everything about silvicultural and harvest technology. According to the underlying model structure, the economic choice of the forest owner is embedded in the objectives and their order, into the production factors and into the production functions which are all given. Choice means to find out the maximum or the optimal solution in the set of given factors and given objectives (Kirzner, 1979).

But the discovery procedure of competition needs the discoverer. As we pointed out in the fourth section of this chapter, the economic facts are not given but are the results of competition. Thus, although economic optimization is helpful for efficient allocation, it is only the second phase of human action. Before optimization can start, the identifying of objectives, products, production factors and production functions is necessary because these facts are not given. This part of discovery is called the phase of entrepreneur action (Kirzner, 1979).

Figure 2.3 illustrates the two phases of human action with the help of the structure of a Faustmann model: It shows the separation of human action into an entrepreneurial phase, in which the means and ends are discovered, and an economic phase, in which the means and ends are optimally allocated, where LEV is the land expectation value, P_j is the price of product class j, W_j is

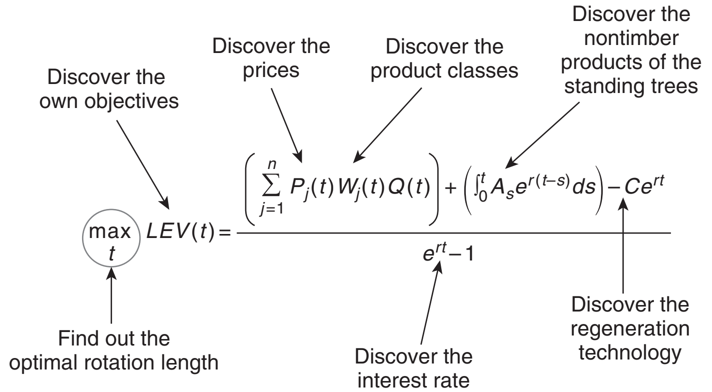

Figure 2.3 The distinction of human action into an entrepreneur phase and an economic phase, exemplified with the help of the structure of a Faustmann model.

the percentage of the product class j in the stand volume, Q is the total stand volume, A is the net revenue for the nontimber product of the standing trees, C is the regeneration cost, r is the interest rate, j is the number for a product class, t is the rotation length and s is the stand age with $s \leq t$.

The distinction of human action into an entrepreneur phase, in which the means and ends are discovered, and an economic phase, in which the means and ends are optimally allocated, is clearly an analytical tool. Every human is an entrepreneur and an economic person at the same time (Kirzner, 1979).

By studying the body of literature in the field of forestry economics with reference to market exchange, it is easy to see that the underlying model of human action focuses on the economic phase. Only a small amount of this literature deals with entrepreneurial aspects, such as Anderson and Leal (2001).

Conclusion

In this chapter, there is no presentation of catallactics as a unified, settled body of thought as the forest economist is accustomed to with the Faustmann school of thought. Instead, catallactics is more a progressive research program (Boettke, 2010, p. 159). Therefore, in this chapter, the main theoretical concepts of catallactics are combined with examples from the field of forestry-related research. This should be interpreted as an invitation to systematically inquire into the inner structure of the gigantic network of human exchanges. This comprises methodical challenges. One is the change in the point of view of what a theory of market coordination can explain because 'the predictive power of this theory is necessarily constrained to a prediction of the type of structure . . . that will result; it does not, however, extend to a prediction of particular events' (Hayek, 2002, p. 11). Another methodical job is the transformation of principally structural insight into operational theory, and lastly, to find ways for testing theorems empirically (Coyne, 2010, p. 26; Smith, 2006, p. 3; Boettke, 2010, p. 164f).

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Notes

1 This slogan I noted at the Hayek lecture 'Hayek and Experimental Economics' by Vernon Smith in Freiburg, Germany, 27 June 2008.
2 The emphasis is found only in the German original of the paper (Hayek, 1968/2003, p. 142) but not in the English translation.

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3

THE GENERALIZED FAUSTMANN FORMULA

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Abstract

This chapter examines the four core areas of the generalized Faustmann formula – the management of even-aged natural stands, even-aged plantations and uneven-aged stands, as well as the development of Pressler's indicator rate formula. Under the generalized formula, stumpage prices, stand volumes, annual incomes, regeneration costs and interest rates could vary from timber crop to timber crop. As a result, the optimal management of even-aged and uneven-aged stands also could vary from timber crop to timber crop. The optimal conditions for the decision variables are derived and their economic meanings explained. Although similar to those obtained under the classic Faustmann formula, the optimal conditions under the generalized Faustmann formula offer much broader and richer interpretations. The increment in stumpage value is shown to consist of price increment, quality increment and quantity increment. The results of comparative statics analysis showed that under the generalized Faustmann formula it is possible to untangle the impacts of changes in current and future production parameters and produce much sharper results. Pressler's indicator rate formula is also shown to maximize the land expectation value under the generalized Faustmann formula. The chapter closes with observations on ongoing efforts and future research opportunities.

Keywords

Generalized Faustmann formula, dynamic programming, even-aged management, uneven-aged management, Pressler's indicator rate formula, price increment, quality increment, quantity increment, comparative statics analysis

Introduction

For nearly 150 years the literature on the determination of optimal rotation age (see Newman, 2002, for a comprehensive compilation of the literature until that time) has relied on the classic Faustmann formula first advanced by Martin Faustmann (1849). In the economic literature, the optimal rotation problem is known as the tree-cutting problem or the wine-storage problem.

Over the years, it has attracted the attention of two Nobel laureates (Ohlin, 1921; Samuelson, 1976). Recognizing that stumpage prices, stand volume, regeneration cost and interest rate do not stay the same rotation after rotation, Chang (1998) developed the generalized Faustmann formula by allowing these factors to vary from harvest period to harvest period. In this chapter, four core areas of the generalized Faustmann formula – the management of (1) even-aged natural stands, (2) even-aged plantations and (3) uneven-aged stands, plus (4) the development of Pressler's indicator rate formula – will be addressed. As will be shown subsequently, these relaxations provide the generalized Faustmann formula with much greater flexibility and produce much richer analytical results.

Under the first topic, the question of optimal harvest age for even-aged natural stands will be examined. Given that about 93% of the world's forests are some type of natural stand (FAO, 2012), this topic is highly pertinent. The condition of reaching optimal harvest age will be examined along with a graphic analysis of the impact of changes in various production parameters. In addition, the total increment in stumpage value will be separated into price increment, quality increment and quantity increment. The relationship among the various formulas of optimal harvest age determination will also be discussed.

The second topic addresses the determination of optimal planting density and harvest age. With most of the industrial roundwood coming from plantations, its proper management is becoming ever more important and deserves careful examinations. The impact of changes in both current and future production parameters on the management decision variables will then be examined through comparative statics analysis.

Under the third topic, the generalized Faustmann formula for uneven-aged management will be developed. It will be shown that the formula resembles that of even-aged plantation management. With both management systems sharing the same theoretical foundation, further analyses are no longer needed. All of the analytical results for the management of even-aged plantations can be readily applicable to that of uneven-aged stands.

Under the fourth topic, Pressler's indicator rate formula will be shown to also represent the optimal condition for the generalized Faustmann formula. The chapter closes with observations on some current developments and future research opportunities.

The generalized Faustmann formula for even-aged natural stand management

Of the 4 billion hectares of forest in the world, 36% is primary forests and 57% is other naturally regenerated forests (FAO, 2012). Most of these forests are managed extensively as even-aged stands. After a clearcut, the stand is typically regenerated naturally, with or without incurring some expenses. The key management question thus revolves around how long one should wait before harvesting the new stand. As the simplest form of even-aged management, it will be discussed first.

Let

$$V_i(t_i) = \sum_{j=1}^{n} P_{ij}(t_i) W_{ij}(t_i) Q_i(t_i)$$

be the stumpage value of the ith timber crop at age t_i, with $\frac{\partial V_i(t_i)}{\partial t_i} > 0$ and $\frac{\partial^2 V_i(t_i)}{\partial t^2} < 0$. $P_{ij}(t_i)$ is the stumpage price of ith timber crop at age t_i for product class j. For example, in the US South, southern pine timber stands typically consist of pulpwood, chip-and-saw timber and sawtimber.

$W_{ij}(t_i)$ is the percentage of the product class j at age t_i of the ith stand volume,
$Q_i(t_i)$ is the total stand volume at age t_i and the volume of a particular product class, $Q_{ij}(t_i) = W_{ij}(t_i)Q_i(t_i)$,
$A_i(s_i)$ is the net annual income for age s_i, $0 \le s_i \le t_i$ of the ith timber crop,
C_i is the regeneration cost for the ith timber crop,
r_i is the interest rate associated with the ith timber crop and
LEV_i is the land expectation value at the beginning of the ith timber crop.

To maximize the value of the land, we want to maximize the present value of profits from growing an infinite number of timber crops.

$$Max\, LEV_1 = \sum_{i=1}^{\infty}\left[V_i(t_i) + \sum_{s_i=1}^{t_i} A_i(s_i)\exp(r_i(t_i - s_i)) - C_i\exp(r_i t_i)\right]\exp\left(\sum_{j=1}^{i} -r_j t_j\right) \tag{1}$$

Note that as a special case, if all $V_i(t_i)$, $A_i(s_i)$, C_i and r_i remain the same for all timber crops, then equation (1) can be expressed as

$$\begin{aligned} LEV_1 &= \left[V_1(t_1) + \sum_{i=1}^{t_1} A_1(s_1)\exp(r_1(t_1 - s_1)) - C_1\exp(r_1 t_1)\right]\left[\exp(-r_1 t_1) + \exp(-2r_1 t_1) + \cdots\right] \\ &= \left[V_1(t_1) + \sum_{i=1}^{t_1} A_1(s_1)\exp(r_1(t_1 - s_1)) - C_1\exp(r_1 t_1)\right]\Big/\left(\exp(r_1 t_1) - 1\right) \end{aligned} \tag{2}$$

and collapses to equation (2) as the classic Faustmann formula. Note also that equation (1) includes the Hartman (1976) formula as a special case. For easy comprehension, equation (1) can also be written as

$$\begin{aligned} Max\, LEV_1 &= \left[V_1(t_1) + \sum_{s_1=1}^{t_1} A_1(s_1)\exp(r_1(t_1 - s_1)) - C_1\exp(r_1 t_1)\right]\exp(-r_1 t_1) \\ &\quad + LEV_2\exp(-r_1 t_1) \end{aligned} \tag{3}$$

In the previous equations the term 'timber crop' should be broadly interpreted. If future crops remain in forestry, they are naturally timber crops. If in the future, the land is switched to growing fruit trees, it would still be viewed as a timber crop. In this case, the income from annual fruit production becomes much more important, whereas that from the final harvest to replace the old fruit trees becomes far less important. Even in the case of conversion to annual crop production or real estate development, there are simply no timber crops in the future. Only the annual net incomes are involved. It should also be noted that over time, the timber crop species could change, for example, from southern pine to hardwood or from spruce to Douglas-fir. It could also change from timber production to fruit production or crop production and vice versa. The generalized Faustmann formula, therefore, could accommodate land-use changes by permitting different types of crops, may they be timber, fruit or grain, for different harvest periods. In the first case, the value of the timberland is determined endogenously, whereas in the latter cases, with land-use change under the generalized Faustmann formula, the value of the land in the future, as LEV_2 in equation (3), is determined exogenously as shown by Klemperer and Farkas (2001).

Equation (3) represents the famous recurrence relation of dynamic programming. In this equation, LEV_1 and LEV_2 represent the objective functions, and the expression

$\left[V_1(t_1)+\sum_{s_1=1}^{t_1}A_1(s_1)\exp(r_1(t_1-s_1))-C_1\exp(r_1t_1)\right]\exp(-r_1t_1)$ represents the payoff associated with the decision variable t_1. Theoretically, equation (3) can be solved with the forward recursive solution method. However, such a solution would involve infinite numbers of stumpage prices, stand volumes, annual incomes or expenses, regeneration costs and interest rates, thus making it impractical. Fortunately, LEV_2 represents just a single value. It embodies all the optimal harvest age decisions for future timber crops that give rise to this specific value. Forest owners and/or managers need not know the details of these decisions, just that they give rise to the specific value. Therefore, solving for the optimal harvest age empirically would involve the insertion of a specific value of LEV_2 into equation (3) to solve for t_1. Such a value could be gleaned from various timberland transactions if there is an active timberland market. Or it could be chosen judiciously to determine the resulting harvest age for the first timber crop under various future values for the timberland.

On reaching the optimal harvest age

In addition to finding the optimal harvest age under equation (3), it is important to understand the economic meaning of reaching the optimal harvest age because it affords the opportunity to determine stepwise year by year the harvest decision by comparing the marginal benefit with the marginal cost of waiting. At the optimal t_1

$$\begin{aligned}\frac{\partial LEV_1}{\partial t_1}=&\left[\frac{\partial V_1(t_1)}{\partial t_1}+r_1\sum_{s_1=1}^{t_1}A_1(s_1)\exp(r_1(t_1-s_1))+A_1(t_1)-C_1r_1\exp(r_1t_1)\right]\exp(-r_1t_1)\\&+\left[V_1(t_1)+\sum_{s_1=1}^{t_1}A_1(s_1)\exp(r_1(t_1-s_1))-C_1\exp(r_1t_1)\right](-r_1)\exp(-r_1t_1)\\&+LEV_2(-r_1)\exp(-r_1t_1)=0\end{aligned}\tag{4}$$

$$\frac{\partial V_1(t_1)}{\partial t_1}+A_1(t_1)=r_1V_1(t_1)+r_1LEV_2\tag{5}$$

Equation (5) states that at the optimal harvest age, the extra amount of stumpage value earned by waiting one more year plus the extra annual income on the left-hand side of the equation must equal the cost of holding the trees plus the cost of holding the land on the right-hand side of the equation. When the left-hand side of equation (5) is greater than the right-hand side, one should wait another year. Conversely, the stand should be harvested. In the interest of brevity, no empirical examples for this topic will be presented. Readers interested in such examples are referred to Chang (1998).

The separation of the stumpage value increment

What is the benefit of waiting? Pressler (1860) pointed out that the stumpage value increment $\frac{\partial V_1(t_1)}{\partial t_1}$ consists of three types of increments when the harvest age is delayed one time period. They are the quantity increment (*Quantitätszuwachs*), the quality increment (*Qualitätszuwachs*) and, lastly, the price increment (*Teuerungszuwachs*). Over the years, these increments have been mentioned in various textbooks; however, it was Chang and Deegen (2011) who separated these satisfactorily both analytically and empirically. Given that

$$\frac{\partial V_1(t_1)}{\partial t_1} = \sum_{j=1}^{n}\left\{\frac{\partial P_{1j}(t_1)}{\partial t_1}W_{1j}(t_1)Q_1(t_1) + P_{1j}(t_1)\frac{\partial W_{1j}(t_1)}{\partial t_1}Q_1(t_1) + P_{1j}(t_1)W_{1j}(t_1)\frac{\partial Q_1(t_1)}{\partial t_1}\right\} \tag{6}$$

$\sum_{j=1}^{n} P_{1j}(t_1)W_{1j}(t_1)Q_1'(t_1)$, the increase in stand value as a result of total stand volume increment, represents the quantity increment. The gain realized from changes in the composition of different product classes of the stand volume $\sum_{j=1}^{n} P_{1j}(t_1)W_{1j}'(t_1)Q_1(t_1)$ represents the quality increment. Finally, the gain realized from changes in prices of different product classes, $\sum_{j=1}^{n} P_{1j}'(t_1)W_{1j}(t_1)Q_1(t_1)$, represents the price increment. It should be noted that in some instances, the quality increment may not matter. For example, in the emerging biomass for energy market, sometimes no quality is recognized. In such a case, the quality increment simply falls out, and only price and quantity increments remain.

In practice, the growth in stumpage value over time can be determined by

$$\begin{aligned} V_1(t_1+1) - V_1(t_1) = \sum_{j=1}^{n}[P_{1j}(t_1+1) - P_{1j}(t_1)]W_{1j}(t_1+1)Q_1(t_1+1) + \sum_{j=1}^{n} P_{1j}(t_1)[W_{1j}(t_1+1) \\ -W_{1j}(t_1)]Q_1(t_1+1) + \sum_{j=1}^{n} P_{1j}(t_1)W_{1j}(t_1)\,[Q_1(t_1+1) - Q_1(t_1)] \end{aligned} \tag{7}$$

Dividing $V_1'(t_1)$ by $V_1(t_1)$ results in

$$\frac{V_1'(t_1)}{V_1(t_1)} = \frac{\sum_{j=1}^{n} P_{1j}'(t_1)W_{1j}(t_1)Q_1(t_1)}{V_1(t_1)} + \frac{\sum_{j=1}^{n} P_{1j}(t_1)W_{1j}'(t_1)Q_1(t_1)}{V_1(t_1)} + \frac{\sum_{j=1}^{n} P_{1j}(t_1)W_{1j}(t_1)Q_1'(t_1)}{V_1(t_1)} \tag{8}$$

with the three terms on the right-hand side of equation (8) being the rates of price increment, quality increment and quantity increment, respectively. Among them, the last two increments in equation (8) are usually positive and under the control of a forester. Price increment or the rate of price increment, however, as Pressler warned, could be either positive or negative depending on the overall economy, specific technological developments or market conditions. For an example of separating these three increments empirically, the readers are referred to Chang and Deegen (2011).

Comparative statics analyses of the impact of changes in stumpage price levels, regeneration cost, annual income and regeneration cost

How will the current versus future changes in stumpage prices, annual income, regeneration cost and interest rate affect the optimal harvest age of the current timber crop? These analyses are important because they will show a priori how the optimal harvest age will be affected before any empirical analyses. Here the impact of these changes will be analyzed graphically. Mathematical analyses of the impact of these changes are available in Chang (1998). To analyze graphically the impact of changes in production factors both currently and in the future, first rewrite equation (5) as

$$\frac{V_1'(t_1) + A_1(t_1)}{V_1(t_1) + LEV_2} = r_1 \tag{9}$$

and name the left-hand side as the rate of marginal revenue growth (RMRG). As the timber stand ages, $V_1'(t_1)$ gradually declines. The numerator of the RMRG approaches $A_1(t_1)$, and the denominator increases and approaches the sum of the limit of $V_1(t_1)$ plus LEV_2. As shown in Figure 3.1, the RMRG curve gradually trends downward. On the other hand, the interest rate line is shown as a flat line. The point where these two curves cross is the optimal harvest age. With this graph, one can quickly see that a higher regeneration cost for the current timber crop, as a sunk cost, has no effect on the optimal harvest age of the current timber crop. On the other hand, a higher stumpage price level for the current timber crop would impact both the numerator and denominator of RMRG. When $V'(t)/V(t)$ is greater than r, higher stumpage prices would raise the current harvest age and vice versa. A higher annual income, on the other hand, would always move the RMRG curve up and raise the current harvest age. Finally, a higher current interest rate would simply move the interest rate line up and result in a lower harvest age for the current timber crop.

The impacts of all the changes in the production factors of future timber crops are reflected through LEV_2. For example, a higher stumpage price level for any of the future timber crops would result in a higher LEV_2 and consequently a smaller RMRG. A downward move of the RMRG curve will then lead to a lower harvest age for the current timber crop. The same is true for higher annual incomes for any of the future timber crops. On the other hand, a higher interest rate or a higher regeneration cost for any of the future timber crops would translate into a smaller LEV_2 and result in a bigger RMRG. As such, they will both lead to a higher harvest age for the current timber crop.

Table 3.1 summarizes the results of all of the comparative statics analyses and also compares these results with those under the classic Faustmann formula. Indeed, the generalized Faustmann formula yields much richer results. Under the classic Faustmann formula, a higher stumpage price level would always shorten the rotation. Yet under the generalized Faustmann formula, a higher current stumpage price level would either raise or lower the current harvest age, whereas a higher future stumpage price level would lower the current harvest age. Whereas

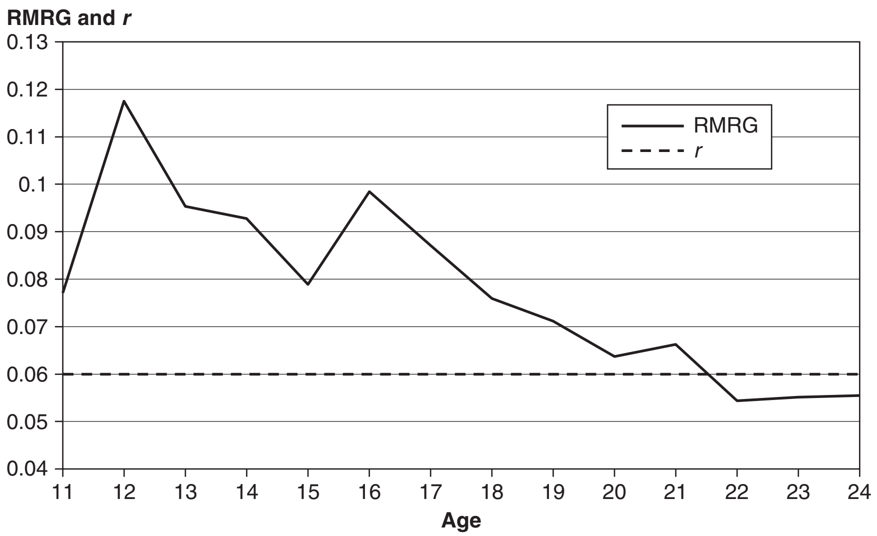

Figure 3.1 Rate of marginal revenue growth (RMRG) and interest rate r.

Table 3.1 The results of comparative statics analyses under the classic Faustmann formula and the generalized Faustmann formula.

Cause	*Effect*
Under classic Faustmann formula	
A one-time increase in	optimal rotation age t
C generation cost	increase
α in $\alpha P(t)$ stumpage price level	increase
β in $\beta A(s)$ annual income	increase if $A(s) < A(t)$ for all s no change if $A(s) = A(t)$ for all s decrease if $A(s) > A(t)$ for all s
r, interest rate	decrease
Under generalized Faustmann formula	
A one-time increase in	
Current timber crop	
C_k, regeneration cost	no change
α_k of $\alpha_k P_k(t_k)$, stumpage price level	
if $\dfrac{\partial V_1(t_1)}{\partial t_1} > r_1 V_1(t_1)$	increase
if $\dfrac{\partial V_1(t_1)}{\partial t_1} < r_1 V_1(t_1)$	decrease
β_k of $\beta_k A_k(s_k)$, annual income	increase
r_k, interest rate	decrease
Future timber crop	
C_n, regeneration cost	increase
α_n of $\alpha_n P(t_n)$, stumpage price level	decrease
β_n of $\beta_n A_n(s_n)$, annual income	decrease
r_n, interest rate	increase

a higher regeneration cost would raise the rotation age under the classic Faustmann formula, only a higher future regeneration cost would do so under the generalized Faustmann formula. Current regeneration cost under the generalized Faustmann formula, as a sunk cost, has no impact on the optimal harvest age. The impact of higher annual income levels under the classic Faustmann formula depends on whether $A_i(s_i)$ is an increasing or decreasing function of stand age. On the other hand, under the generalized Faustmann formula, the higher level of current annual income would raise the current harvest age, whereas higher levels of annual incomes in future timber crops would have the opposite effect. Lastly, a higher interest rate under the classic Faustmann formula lowers the optimal rotation age. Under the generalized Faustmann formula, a higher current interest rate lowers the optimal harvest age, whereas a higher future interest rate raises the optimal harvest age.

Other formulas of optimal harvest age determination and their relationship with the generalized Faustmann formula

Over the years, other formulas have been proposed to determine the optimal harvest age. Chief among them are the present net worth (PNW) formula, which maximizes the present value of the profit from growing just one crop of timber:

$$PNW = V_1(t_1)\exp(-r_1 t_1) - C_1$$

the forest rent (FR) formula of maximizing:

$$FR = [V_1(t_1) - C_1]/t_1$$

and the biological formula of maximizing the mean annual increment (MAI):

$$MAI = Q_1(t_1)/t_1$$

Regarding the relationship between LEV_1 and PNW, note that when all the annual incomes $A_i(s_i)$ of the current timber crop as well as LEV_2 – the present value of all incomes and expenses from future timber crops – are ignored, then LEV_1 becomes PNW. Given that the PNW formula ignores the cost of holding the land, it will lead to an optimal harvest age that is higher than that from the generalized Faustmann formula.

The relationship between the generalized Faustmann formula and the FR formula is examined through the land rent (R). Note that when all the annual incomes $A_i(s_i)$ are ignored,

$$R = r_1[V_1(t_1) - C_1\exp(r_1 t_1) + LEV_2]\exp(-r_1 t_1)$$

Applying L'Hopital's rule when r_1 approaches 0,

$$\begin{aligned}\lim_{r_1 \to 0} R &= \frac{\lim_{r_1 \to 0} r_1\left[V_1(t_1) - C_1\exp(r_1 t_1) + LEV_2\right]}{\lim_{r_1 \to 0} \exp(r_1 t_1)} \\ &= \frac{\lim_{r_1 \to 0}\left\{[V_1(t_1) - C_1\exp(r_1 t_1) + LEV_2] + r_1[-C_1 t_1 \exp\left(r_1 t_1\right)]\right\}}{\lim_{r_1 \to 0} t_1 \exp(r_1 t_1)} \\ &= [V_1(t_1) - C_1]/t_1 = FR \text{ when } LEV_2 = 0\end{aligned}$$

That is to say, R collapses to FR when all the annual incomes are ignored, $LEV_2 = 0$ and interest rate r_1 also equals 0. Given that when LEV_1 is maximized the land rent is also maximized, only when the previous conditions are satisfied will the FR formula result in the correct optimal harvest age.

For the biological formula of MAI maximization, note that when $P_1(t_1) = k$ and $C_1 = 0$, then

$$FR = \frac{P_1(t_1)Q_1(t_1) - C_1}{t_1} = \frac{kQ_1(t_1)}{t_1} = kMAI$$

That is to say, when all the annual incomes are ignored; LEV_2, interest rate r_1 and regeneration cost C_1 all equal to 0; and the stumpage prices of trees of different ages are all the same, implying that there is no premium for older and therefore larger diameter trees, then R collapses to MAI, and the MAI formula results in the correct optimal harvest age.

The generalized Faustmann formula for even-aged plantation management

Timber plantations now account for 7% of the forests in the world (FAO, 2012). Despite this relatively small percentage, in recent decades these plantations have been producing an ever-increasing amount of industrial roundwood supplies. Large acreages of pine plantations have been established in the US South, Brazil, Chile and New Zealand, as well as extensive Chinese fir plantations in China. Eucalyptus plantations have been established in Brazil, China, Australia and several Southeast Asian countries. Red pine and spruce plantations have been established widely in Europe. In the future, energy plantations could also emerge to play an important role in sequestering carbon dioxide emissions. More importantly, these plantations with their high productivity assure the possibility of conserving natural forests and ecosystems.

For even-aged plantations, both the harvest age and the initial planting density must be determined simultaneously. In this section, the notations defined earlier are expanded as follows:

$P_i(t_i, n_i)$ is the stumpage price for the *j*th product class of the *i*th plantation established with an initial planting density of n_i at age t_i.
$W_{ij}(t_i,n_i)$ is the percentage of the *j*th product class of the *i*th plantation established with an initial planting density of n_i at age t_i.
$Q_i(t_i, n_i)$ is the stand volume of the *i*th plantation established with an initial planting density of n_i at age t_i.
$V_i(t_i,n_i)=\sum_{j=1}^{n} P_{ij}(t_i,n_i)W_{ij}(t_i,n_i)Q_i(t_i,n_i)$ is the stumpage value of the *i*th plantation with an initial planting density of n_i at age t_i, with $\frac{\partial V_i(t_i,n_i)}{\partial t_i}>0, \frac{\partial V_i(t_i,n_i)}{\partial n_i}>0$ and $\frac{\partial^2 V_i(t_i,n_i)}{\partial t_i^2}<0, \frac{\partial^2 V_i(t_i,n_i)}{\partial n_i^2}<0$.
Cs_i stands for the site preparation cost for the *i*th plantation.
Cp_i stands for the cost of planting per seedling, including the cost of both the labor and seedling.
All other variables are as defined previously.

Following equation (3), the generalized Faustmann land expectation value formula for plantation management can be expressed as

$$LEV_1=\left[V_1(t_1,n_1)+\int_0^{t_1} A_1(s_1)\exp(r_1(t_1-s_1))ds_1-(Cs_1+Cp_1n_1)\exp(r_1t_1)\right]\exp(-r_1t_1)$$
$$+LEV_2\exp(-r_1t_1) \tag{10}$$

$$\frac{\partial LEV_1}{\partial t_1}=\left[\frac{\partial V_1(t_1,n_1)}{\partial t_1}+r_1\int_0^{t_1} A_1(s_1)\exp(r_1(t_1-s_1)ds_1+A_1(t_1)-(Cs_1+Cp_1n_1)r_1\exp(r_1t_1)\right]$$
$$\exp(-r_1t_1)+\left[V_1(t_1,n_1)+\int_0^{t_1} A_1(s_1)\exp(r_1(t_1-s_1)ds_1-(Cs_1+Cp_1n_1)\exp(r_1t_1)\right]$$
$$(-r_1)\exp(-r_1t_1)-r_1\exp(-r_1t_1)LEV_2=0 \tag{11}$$

$$\frac{\partial LEV_1}{\partial n_1}=\left[\frac{\partial V_1(t_1,n_1)}{\partial n_1}-Cp_1\exp(r_1t_1)\right]\exp(-r_1t_1)=0 \tag{12}$$

For notational simplicity, $\sum_{s_1=1}^{t_1} A_1(s_1)\exp(r_1(t_1-s_1))$ is replaced by $\int_0^{t_1} A_1(s_1)\exp(r_1(t_1-s_1))ds_1$. To maximize LEV_1, from equation (11):

$$\frac{\partial V_1(t_1,n_1)}{\partial t_1} + A_1(t_1) - r_1 V_1(t_1,n_1) - r_1 LEV_2 = 0 \tag{13}$$

from equation (12):

$$\frac{\partial V_1(t_1,n_1)}{\partial n_1} - Cp_1 \exp(r_1 t_1) = 0 \tag{14}$$

Equation (13) states that at optimal harvest age, the extra stumpage value plus the extra annual income earned by waiting one more year must equal the cost of holding the trees plus the cost of holding the land, similar to the case of even-aged natural stand management discussed earlier. Equation (14) suggests that at the optimal planting density, the extra stumpage value earned by planting an additional tree must equal the extra cost of planting the extra tree compounded to the end of the harvest period.

Table 3.2 presents an example of the simultaneous determination of optimal harvest age and planting density with an interest rate of 5.5% for the first harvest period, a site preparation cost of US\$160 per acre and a planting cost of US\$0.10 per tree, including the cost of the seedling and labor for planting, with no annual income and a future land value of US\$800 per acre. Stumpage prices are US\$80 per cord for chip-and-saw logs and US\$28 per cord for pulpwood, with 76 cubic feet of solid wood per 128 cubic feet (4' × 8' × 8') of stacked volume. Given these parameters, the optimal planting density will be 700 trees per acre and optimal harvest age will be 26 years.

Comparative statics analysis of the generalized Faustmann formula for even-aged plantations

To carry out comparative statics analyses, the second-order conditions for the optimal combination of t_1 and n_1 must be established first.

$$\begin{aligned}\frac{\partial^2 LEV_1}{\partial t_1^2} &= \left[\frac{\partial^2 V_1(t_1,n_1)}{\partial t_1^2} + \frac{\partial A_1(t_1)}{\partial t_1} - r_1 \frac{\partial V_1(t_1,n_1)}{\partial t_1}\right]\exp(-r_1 t_1) \\ &\quad + \left[\frac{\partial V_1(t_1,n_1)}{\partial t_1} + A_1(t_1) - r_1 V_1(t_1,n_1) - r_1 LEV_2\right](-r_1)\exp(-r_1 t_1) \\ &= \left[\frac{\partial^2 V_1(t_1,n_1)}{\partial t_1^2} + \frac{\partial A_1(t_1)}{\partial t_1} - r_1 \frac{\partial V_1(t_1,n_1)}{\partial t_1}\right]\exp(-r_1 t_1) < 0\end{aligned} \tag{15}$$

Equation (15) is less than 0 because the terms inside the bracket on the second line are the first-order condition for optimal t_1 and equal 0.

$$\frac{\partial^2 LEV_1}{\partial n_1^2} = \frac{\partial^2 V_1(t_1,n_1)}{\partial n_1^2}\exp(-r_1 t_1) < 0 \tag{16}$$

Table 3.2 The simultaneous determination of optimal planting density and harvest age.

Planting density (trees per acre)		*Harvest age (years)*							
		21	22	23	24	25	26	27	28
400	Cords of C&S	15.46	17	18.72	20.92	22.63	24.2	26.14	27.35
	Cords of pulpwood	12.6	12.61	12.99	12.17	12.08	12.68	12.28	12.29
	Stumpage value/A	1,589.71	1,713.31	1,861.49	2,013.92	2,148.67	2,291.39	2,435	2,532.37
	LEV/Acre	552.90	549.46	551.18	551.70	545.54	539.80	532.74	514.40
500	Cords of C&S	14.92	16.44	18.36	21.01	22.65	24.28	26.27	28.42
	Cords of pulpwood	14.94	14.94	15.3	14.43	14.69	14.79	14.83	14.53
	Stumpage value/A	1,611.59	1,749.72	1,897.42	2,085.16	2,223.08	2,399.61	2,516.34	2,680.58
	LEV/Acre	549.79	530.32	551.32	560.73	554.35	555.70	541.16	536.17
600	Cords of C&S	14.46	16.13	18.61	20.72	22.75	24.46	26.27	28.28
	Cords of pulpwood	16.97	17	17.11	16.45	16.67	16.74	16.87	16.53
	Stumpage value/A	1,632.24	1,766.37	1,968.05	2,117.95	2,286.24	2,425.91	2,573.94	2,725.03
	LEV/Acre	546.30	545.28	561.25	559.49	560.32	551.99	544.21	535.70
700	Cords of C&S	13.87	15.69	18.5	20.48	21.94	24.68	26.59	28.21
	Cords of pulpwood	18.93	19.37	18.45	18.14	18.85	19.1	18.36	18.12
	Stumpage value/A	1,639.46	1,797.58	1,996.58	2,146.29	2,282.91	2,509	2,641.03	2,763.8
	LEV/Acre	538.57	544.59	559.30	557.06	549.08	561.87	549.40	534.01
800	Cords of C&S	13.39	15.16	18.19	20.02	22.04	24.14	26.29	28.53
	Cords of pulpwood	20.68	21.11	20.24	20.49	20.7	20.66	20.16	19.91
	Stumpage value/A	1,650.5	1,803.78	2,021.56	2,174.61	2,343.02	2,509.88	2,667.35	2,840.2
	LEV/Acre	532.05	536.44	556.36	554.62	554.68	552.08	545.36	540.39

Stumpage price for chip and saw (C&S) = US$80/cord, pulpwood = US$28/cord, Cs_1 = US$160/A, Cp_1 = US$0.10/tree.
Interest rate = 5.5%, and LEV_2 = US$800/acre.

and

$$D = \begin{vmatrix} \partial^2 LEV_1 / \partial t_1^2 & \partial^2 LEV_1 / \partial t_1 \partial n_1 \\ \partial^2 LEV_1 / \partial t_1 \partial n_1 & \partial^2 LEV_1 / \partial n_1^2 \end{vmatrix}$$
$$= (\partial^2 LEV_1 / \partial t_1^2)(\partial^2 LEV_1 / \partial n_1^2) - (\partial^2 LEV_1 / \partial t_1 \partial n_1)^2 > 0 \tag{17}$$

as part of the second-order conditions.

It should be noted that

$$\frac{\partial^2 LEV_1}{\partial t_1 \partial n_1} = [\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1 - Cp_1 r_1 \exp(r_1 t_1)]\exp(-r_1 t_1) + [\partial V_1(t_1, n_1) / \partial n_1$$
$$- Cp_1 \exp(r_1 t_1)](-r_1)\exp(-r_1 t_1)$$
$$= \partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1 \exp(-r_1 t_1) - Cp_1 r \tag{18}$$

because the terms of the second line are the first-order condition for the optimal n_1. Thus, although equation (17) must be true, a priori nothing is said about the sign of $\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1$. Given that $\partial V_1(t_1, n_1) / \partial t_1$ represents the current annual increment in revenue, $\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1 = \partial(\partial V_1(t_1, n_1) / \partial t_1) / \partial n_1$ represents changes in current annual increment in stumpage value as a result of changes in planting density. As Kent and Dress (1980) have shown, plantations of different initial planting densities eventually converge to the same random pattern. As such, given enough time, these stands of different initial planting densities will also converge to the same stand volume, and thus, value. Figure 3.2 shows two of the stumpage value curves and their corresponding current annual increments in stumpage value curves. For the stand with a higher planting density, its current annual increment (CAI) in stumpage value ascends faster, peaks at an earlier age and descends faster thereafter. For the stand with a lower planting density, its CAI ascends slower, peaks at a later age and descends slower thereafter. As shown in Figure 3.2, these two CAI curves will cross each other at an age T. Because the area below the CAI in stumpage value curve stands for the stumpage value, the vertically shaded area represents that period when the higher planting density stand outgrows the lower planting density stand in value. The horizontally shaded area, on the other hand, would represent the opposite case. At an age $\hat{T}$, these two shaded areas would be equal in size, and the two stands would end up with the same stumpage value thereafter. Once the optimal planting density is determined, the relevant CAI in stumpage value curve will be uniquely defined. The critical question, then, is the position of the optimal harvest age t_1 relative to T. If t_1 is less than T, $\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1 > 0$. If t_1 is larger than T, $\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1 < 0$. When t_1 and T coincide, $\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1 = 0$. Thus, there are three possibilities.

Case 1, $\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1 > 0$ and $[\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1]\exp(-r_1 t_1) - Cp_1 r_1 < 0$

Case 2, $\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1 > 0$ and $[\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1]\exp(-r_1 t_1) - Cp_1 r_1 < 0$

Case 3, $\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1 < 0$

As the subsequent analyses demonstrate, the sign of $\partial^2 V_1(t_1, n_1) / \partial t_1 \partial n_1$ plays an important role in discerning the impact of changes in site preparation cost, cost of planting, stumpage price and interest rate.

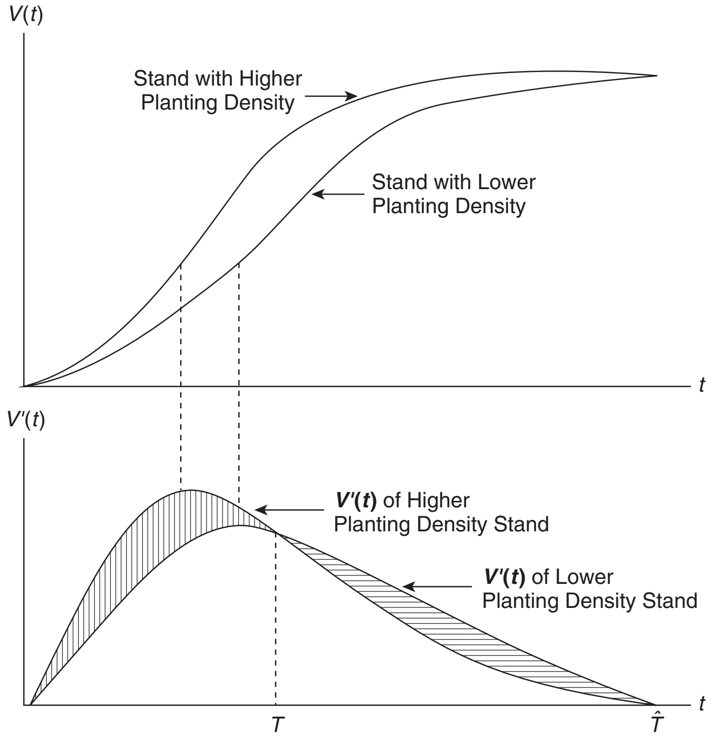

Figure 3.2 Stumpage value and CAI in value of two stands with different planting densities.

The impact of changes in current site preparation cost, Cs_1

As shown in Appendix A-1, $\dfrac{d\,t_1}{d\,Cs_1} = 0$ and $\dfrac{d\,n_1}{d\,Cs_1} = 0$, suggesting that a change in the current site preparation cost, as a sunk fixed cost, affects neither the harvest age nor the planting density of the current timber crop.

The impact of changes in current planting cost, Cp_1

As shown in Appendix A-2,

$$\frac{d\,t_1}{d\,Cp_1} = \frac{-\partial^2 LEV_1 / \partial t_1 \partial n_1}{D} \tag{19}$$

and

$$\frac{d\,n_1}{d\,Cp_1} = \frac{\partial^2 LEV_1 / \partial t_1^2}{D} < 0 \tag{20}$$

From equation (20), $dn_1 / dCp_1 < 0$, suggesting that a higher current planting cost always leads to a lower planting density for the current stand.

The effect of a higher current planting cost on the optimal harvest age of the current stand, on the other hand, depends on the sign and the magnitude of $\partial^2 V_1(t_1,n_1)/\partial t_1 \partial n_1$.

Under case 1, when $\partial^2 V_1(t_1,n_1)/\partial t_1 \partial n_1 > 0$ and $[\partial^2 V_1(t_1,n_1)/\partial t_1 \partial n_1]\exp(-r_1 t_1) - Cp_1 r_1 > 0$, $dt_1/dCp_1 < 0$. Higher planting cost for the current timber crop lowers the optimal harvest age for the current timber crop.

Under case 2, when $\partial^2 V_1(t_1,n_1)/\partial t_1 \partial n_1 > 0$ but $[\partial^2 V_1(t_1,n_1)/\partial t_1 \partial n_1]\exp(-r_1 t_1) - Cp_1 r_1 < 0$, and under case 3, when $\partial^2 V_1(t_1,n_1)/\partial t_1 \partial n_1 < 0$, $dt_1/dCp_1 > 0$, higher planting cost for the current timber crop raises the optimal harvest age for the current timber crop. Whether the impact of higher planting cost on the optimal harvest age is case 1, 2 or 3 can only be determined empirically.

The impact of a higher current stumpage price level across the board, α_1

As shown in Appendix A-3,

$$\frac{dt_1}{d\alpha_1} = \left\{ -\left[\frac{\partial V_1(t_1,n_1)}{\partial t_1} - r_1 V_1(t_1,n_1)\right]\exp(-r_1 t_1)\frac{\partial^2 V_1(t_1,n_1)}{\partial n_1^2}\exp(-r_1 t_1) \right.$$
$$\left. - \frac{-\partial V_1(t_1,n_1)}{\partial n_1}\exp(-r_1 t_1)\left[\frac{\partial^2 V_1(t_1,n_1)}{\partial t_1 \partial n_1}\exp(-r_1 t_1) - Cp_1 r_1\right]\right\}/D \qquad (21)$$

$$\frac{dn_1}{d\alpha_1} = \left\{ (\partial^2 LEV_1/\partial t_1^2)\left(-\left[\frac{\partial V_1(t_1,n_1)}{\partial t_1} - r_1 V_1(t_1,n_1)\right]\exp(-r_1 t_1)\right) \right.$$
$$\left. - \left[\frac{\partial^2 V_1(t_1,n_1)}{\partial t_1 \partial n_1}\exp(-r_1 t_1) - Cp_1 r_1\right]\left(\frac{-\partial V_1(t_1,n_1)}{\partial n_1}\exp(-r_1 t_1)\right)\right\}/D \qquad (22)$$

From equation (21) and (22) we reach the following conclusions.

If $\frac{\partial^2 V_1(t_1,n_1)}{\partial t_1 \partial n_1}\exp(-r_1 t_1) - Cp_1 r_1 > 0$, and $\frac{\partial V_1(t_1,n_1)}{\partial t_1} - r_1 V_1(t_1,n_1) \ge 0$, both $dt_1/d\alpha_1$ and $dn_1/d\alpha_1 > 0$. Higher stumpage price level across the board raises the harvest age and increases the initial planting density. Yet, when $\frac{\partial V_1(t_1,n_1)}{\partial t_1} - r_1 V_1(t_1,n_1) < 0$, both $dt_1/d\alpha_1$ and $dn_1/d\alpha_1$ are uncertain.

If $\frac{\partial^2 V_1(t_1,n_1)}{\partial t_1 \partial n_1}\exp(-r_1 t_1) - Cp_1 r_1 < 0$, and $\frac{\partial V_1(t_1,n_1)}{\partial t_1} - r_1 V_1(t_1,n_1) \ge 0$, both $dt_1/d\alpha_1$ and $dn_1/d\alpha_1$ are uncertain. When $\frac{\partial V_1(t_1,n_1)}{\partial t_1} - r_1 V_1(t_1,n_1) < 0$, both $dt_1/d\alpha_1$ and $dn_1/d\alpha_1 < 0$, meaning higher stumpage prices across the board lower the harvest age and lower the planting density.

The impact of higher annual income

As shown in Appendix A-4, with β_1 representing the level of annual income,

$$\frac{\partial^2 LEV_1}{\partial t_1 \partial \beta_1} = A_1(t_1) \text{ and } \frac{\partial^2 LEV_1}{\partial n_1 \partial \beta_1} = 0$$

$$\frac{dt_1}{d\beta_1} = -A_1(t_1)\left(\frac{\partial^2 LEV_1}{\partial n_1^2}\right) / D > 0 \text{ and}$$

$$\frac{dn_1}{d\beta_1} = -\left(\frac{\partial^2 LEV_1}{\partial t_1 \partial n_1}\right)(-A_1(t_1))/D.$$

That is to say, a higher level of annual income for the current timber crop always raises the harvest age for the current timber crop. Whether such annual income will increase or decrease the planting density depends on the sign of $\left(\frac{\partial^2 LEV_1}{\partial t_1 \partial n_1}\right)$.

The impact of higher interest rate for the current timber crop

As shown in Appendix A-5,

$$\frac{dt_1}{dr_1} = \left[(V_1(t_1, n_1) + LEV_2)\left(\frac{\partial^2 LEV_1}{\partial n_1^2}\right) - Cp_1 t_1 \exp(r_1 t_1)\left(\frac{\partial LEV_1}{\partial t_1 \partial n_1}\right)\right] / D$$

and

$$\frac{dn_1}{dr_1} = \left[\left(\frac{\partial^2 LEV_1}{\partial t_1^2}\right)(Cp_1 t_1 \exp(r_1 t_1)) - \left(\frac{\partial^2 LEV_1}{\partial t_1 \partial n_1}\right)(V_1(t_1, n_1) + LEV_2)\right] / D$$

Whether a higher interest rate for the current timber crop would lower the optimal harvest age depends on the sign of $\left(\frac{\partial^2 LEV_1}{\partial t_1 \partial n_1}\right)$. When it is greater than 0, the optimal harvest age will be lowered. Otherwise, the impact is uncertain and would depend on the magnitude of $\left(\frac{\partial^2 LEV_1}{\partial t_1 \partial n_1}\right)$. Similarly, the optimal planting density also depends on the sign of $\left(\frac{\partial^2 LEV_1}{\partial t_1 \partial n_1}\right)$. When it is greater than 0, a higher interest rate leads to a lower planting density. Otherwise, the impact is uncertain and would depend on the magnitude of $\left(\frac{\partial^2 LEV_1}{\partial t_1 \partial n_1}\right)$.

The impact of higher future land value

As shown in Appendix A-6,

$$\frac{dt_1}{dLEV_2} = r_1\left(\frac{\partial^2 LEV_1}{\partial n_1^2}\right) / D < 0 \text{ and}$$

$$\frac{dn_1}{dLEV_2} = -\left(\frac{\partial^2 LEV_1}{\partial t_1 \partial n_1}\right) r_1 / D.$$

Higher future land value always lowers the optimal harvest age for the current timber crop. Its impact on the optimal planting density for the current timber crop depends on the sign of

$\left(\dfrac{\partial^2 LEV_1}{\partial t_1 \partial n_1}\right)$. When it is greater than 0, a higher future land value will decrease the planting density. Otherwise, it will increase the planting density.

The results of the previous comparative statics analyses are summarized in Table 3.3. A comparison of these results with those under the classic Faustmann formula (Chang, 1983) would indicate that the former produces much richer results regarding changes in the current parameters and clear-cut results regarding the future parameters unavailable under the classic Faustmann formula.

Table 3.3 Summary of comparative statics analyses of the impact of changes on the optimal t and n for even-aged plantation management under the generalized Faustmann formula.

Parameter	$\dfrac{\partial^2 V_1(t_1,n_1)}{\partial t_1 \partial n_1} < 0$	$\dfrac{\partial^2 V_1(t_1,n_1)}{\partial t_1 \partial n_1} > 0$ $\dfrac{\partial^2 V_1(t_1,n_1)}{\partial t_1 \partial n_1}\exp(-r_1 t_1)$ $-Cp_1 r_1 < 0$	$\dfrac{\partial^2 V_1(t_1,n_1)}{\partial t_1 \partial n_1} > 0$ $\dfrac{\partial^2 V_1(t_1,n_1)}{\partial t_1 \partial n_1}\exp(-r_1 t_1)$ $-Cp_1 r_1 > 0$
dt_1/dCs_1	=0	=0	=0
dn_1/dCs_1	=0	=0	=0
dt_1/dCp_1	>0	>0	<0
dn_1/dCp_1	<0	<0	<0
	If $\dfrac{\partial V_1(t_1,n_1)}{\partial t_1} - r_1 V_1(t_1,n_1) \geq 0$		
$dt_1/d\alpha_1$	uncertain	uncertain	>0
$dn_1/d\alpha_1$	uncertain	uncertain	>0
	If $\dfrac{\partial V_1(t_1,n_1)}{\partial t_1} - r_1 V_1(t_1,n_1) < 0$		
$dt_1/d\alpha_1$	<0	<0	uncertain
$dn_1/d\alpha_1$	<0	<0	uncertain
$dt_1/d\beta_1$	>0	>0	>0
$dn_1/d\beta_1$	<0	<0	>0
dt_1/dr_1	uncertain	uncertain	<0
dn_1/dr_1	uncertain	uncertain	<0
$dt_1/dLEV_2$	<0	<0	<0
$dn_1/dLEV_2$	>0	>0	<0